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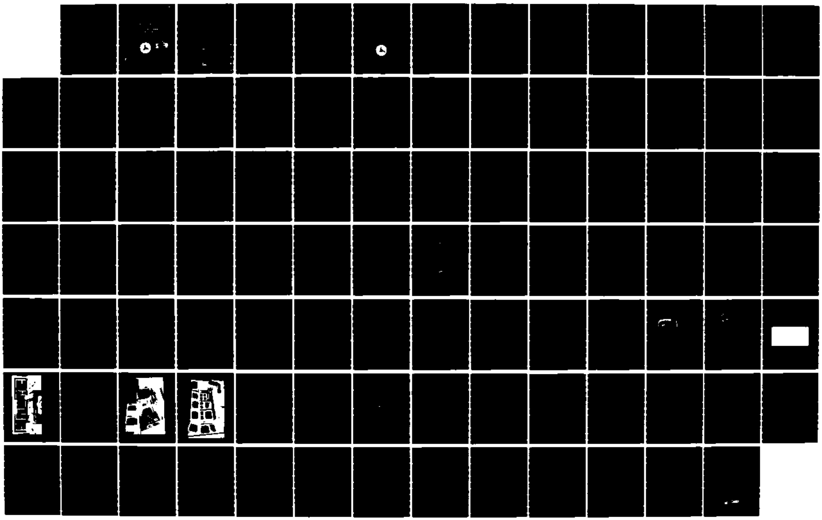

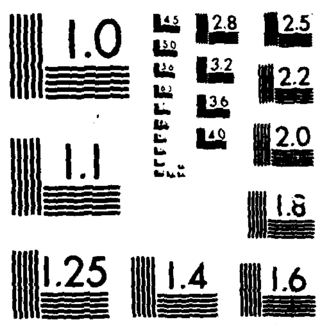

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CAORF TECHNICAL REPORT
SIMULATION EXPERIMENT

APPLICATION OF PRECISION NAVIGATOR SYSTEM IN SANDY HOOK CHANNEL UNDER CONDITIONS OF DEGRADED AIDS-TO-NAVIGATION

DEPARTMENT OF TRANSPORTATION ★ UNITED STATES OF AMERICA ★

U. S. DEPARTMENT OF TRANSPORTATION

MARITIME ADMINISTRATION
OFFICE OF SHIPBUILDING, OPERATIONS
AND RESEARCH

NATIONAL MARITIME RESEARCH CENTER
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NOVEMBER 1985

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Evaluation of advanced navigation systems is part of ongoing simulator research at CAORF. This experiment evaluated the precision navigator (pre-nav) display system in the restricted waters of Sandy Hook Channel. Both analog and digital displays were used. Test subjects operated in two navigational modes: visual-only and visual with precision navigator. Results showed the effectiveness of the pre-nav system under conditions of degraded aids-to-navigation, and demonstrated the advantages in track-keeping over the visual-only mode. In addition, test subjects made several recommendations for improving the safety of navigating in the Sandy Hook Channel under adverse conditions. Several suggestions were made for improving the current aids-to-navigation configurations until such time as pre-nav system is available for shipboard use.

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APPLICATION OF PRECISION NAVIGATOR SYSTEM IN SANDY HOOK CHANNEL UNDER CONDITIONS OF DEGRADED AIDS-TO-NAVIGATION

By

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CHAPTER 1

INTRODUCTION

1.1 PURPOSE

This report describes a simulated navigation experiment in the restricted waters of Sandy Hook. The purpose of the experiment is to evaluate a precision navigator display system (similar to the marine radar interrogator transponder (MRIT) system) as a navigational aid. Test performance was compared in two navigational modes: one using visual-only sighting; the other, visual sighting and the precision navigator display. The experiment was conducted at the Computer Aided Operations Research Facility (CAORF), part of the National Maritime Research Center, Kings Point, New York.

Besides contributing to a broader data base for this type of display system, a secondary purpose of the experiment was to examine the efficiency of present piloting methods under conditions which severely inhibit the use of normal visual cues. The Sandy Hook locale was selected for the scenario because of its heavy ice accumulations. After exposing a number of area pilots to this scenario, recommendations were solicited for stop-gap measures to improve safety of navigation in the Sandy Hook Channel.

1.2 OBJECTIVES OF THE EXPERIMENT

- Study pilot methodologies and use of aids-to-navigation (A/N) for position determination and trackkeeping in restricted waters.
- Evaluate pilot performance as a function of navigational aids available.
- Evaluate pilot ability to develop procedures to safely navigate with degraded A/N conditions.
- Investigate the degree of pilot reliance on unfamiliar navigational equipment.
- Study pilot workload as a function of navigational aids being used.
- Provide data that will be useful in the design of a prototype precision navigator system for shipboard use.
- Elicit pilot recommendations for improving A/N configurations in the Sandy Hook Channel.

1.3 BACKGROUND

Navigators in the vicinity of coastlines and harbor approaches have always made use of visual sightings of landmarks and other aids, such as lighthouses, beacons and buoys. Ship's position is fixed by plotting the intersection of bearing lines from two or more such objects, which are strategically located and accurately displayed on nautical charts.

Pilots, having made many passages in a particular coastal or harbor area, are most familiar with the landmarks, shoals, currents and general weather conditions of the locale. They have committed to memory safe course legs, water depths, the positions of known hazards, and navigational aids. However, their ability to visually estimate ranges and bearings to aids and land masses becomes impaired during periods of limited visibility, at night, or

in cases where frequently used land marks or buoys are missing for whatever cause. Under these conditions, developments in radio electronics have greatly improved navigation techniques and accuracy.

Among the electronic equipment available to help determine ship position in all weather and beyond sight of land are the following:

Open Sea Navigation

- o Satellite navigators
- o Loran
- o Omega

Coastal Navigation

- o Loran
- o Decca
- o Racons
- o Radar

Harbor Piloting

- o Racons
- o Radar
- o Decca
- o Transponders

Such electronic devices complement visual piloting methods in coastal navigation and especially in harbor areas. The precision navigator (pre-nav) displays simulated in this experiment go beyond the above systems, which are presently available for harbor and inland use, and are independent of physical aids to navigation such as buoys, which may be inoperative or off-station due to weather extremes. The pre-nav also precludes time-consuming plotting which is necessary with the other electronic aids.

The pre-nav system provides both digital and analog (graphic) displays. The digital read-out provides the pilot with vessel position relative to the center track line of the channel. The analog display presents information similar to the digital readout, but in a graphic format with information regarding ship position and motion available instantaneously.

In this experiment, the precision navigator was evaluated against visual-only sighting. The results show pilot performance with and without the pre-nav under conditions of clear visibility and degraded aids-to-navigation in the Sandy Hook Channel.

CHAPTER 2

METHODOLOGY

2.1 SIMULATION DESIGN

The experiment was conducted at the Maritime Adminstration's Computer Aided Operations Research Facility (CAORF). This modern simulator facility is described in Appendix A.

2.1.1 Environmental Data Base

The data base used was part of the New York Harbor data base, the most refined and up-to-date data base at CAORF. It provided the visual scene and the precision navigator display information. The specific location chosen was the Sandy Hook Channel from the channel entrance buoys inbound around Sandy Hook to the "10" buoy in Raritan Bay East Reach. The visual scene included all the natural geographic features and many buildings, bridges, and other graphic details. All aids-to-navigation except those modified for the scenario (see Paragraph 2.4.2) were included with their proper characteristics.

2.1.2 Ownship Performance Characteristics

The vessel simulated for these tests was an 80,000 DWT tanker with the following particulars:

- o Length - 233 meters (763 feet)
- o Beam - 38 meters (125 feet)
- o Draft - 9 meters (30 feet)

These characteristics plus other parameters unique to this vessel type, including hydrodynamic, aerodynamic, and engine coefficients, were used in the computer program to produce realistic and accurate motion of the simulated ship.

2.1.3 Bridge Equipment

The bridge equipment included an engine order telegraph/throttle, steering stand with gyro repeater, turn rate indicator, rudder angle indicator, RPM indicator, overhead mounted gyro repeater, pelorus-equipped repeater on each bridge wing, and speed log. This equipment is standard on today's merchant vessels.

2.1.3.1 Precision Navigator Displays

In addition to the above equipment there were two precise navigator displays consisting of two video monitors mounted on the bridge console. One presented the digital display and the other presented the analog display.

The digital display (Figure 2-1) showed Ownship's time, distance off the designated track (in feet, right or left), velocity along the track (in knots), and velocity perpendicular to the track (in feet/minute, right of left). This digital information was derived by the CAORF computer from data available instantaneously on the location of the ship, the location of the turnpoints, and the designated track. The information was highly accurate and located the ship's center of gravity precisely.

The analog display on the second monitor (Figure 2-1) showed location of the

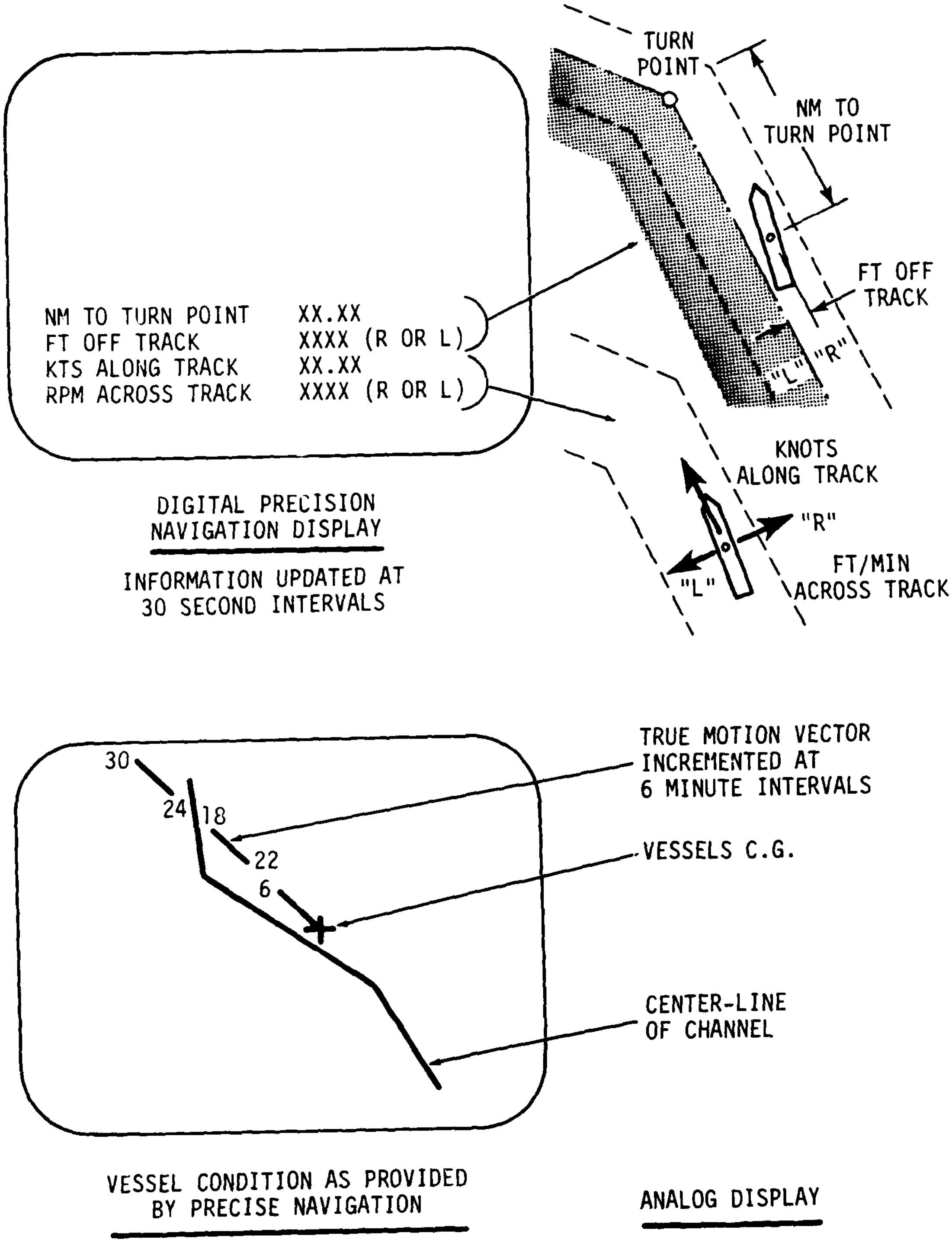

Figure 2-1. Precision Navigator Information Displays

ship's center of gravity with respect to the turnpoints, channel boundaries, and designated track. In addition, the ship's velocity vector provided information regarding the vessel's true motion. These displays were transmitted to the bridge monitors via closed circuit television from a similar display at the CAORF control station.

2.2 EXPERIMENT DESIGN

The precision with which a vessel could be safely navigated through a channel under degraded A/N conditions by pilots familiar with the channel, its predominant currents, and aids-to-navigation, was examined in two modes:

- o Visual-Only
- o Visual with Precision Navigator

In addition to the pilot (test subject), the bridge watch included a licensed mate and a qualified helmsman.

2.2.1 Visual-Only Mode

All runs in this mode were made during daylight hours in unlimited visibility. Eight test subjects were required to make one inbound and one outbound transit each through the segment of Sandy Hook Channel. Many of the buoys were missing due to severe, yet realistic, ice conditions, and no navigational aids were available to the test subjects other than a pelorus mounted on each bridge wing and a standard navigational chart of the area.

2.2.2 Visual With Precision Navigator Mode

The lighting and visibility conditions for pre-nav runs were identical to those of the visual-only mode. Each of eight test subjects executed an inbound and outbound passage through the channel segment under the same degraded A/N conditions as the visual-only runs. No navigational aids were available with the exception of the wing-mounted pelorus used in the visual-only mode, a navigational chart of the area, and the precision navigator display monitors located on the forward console.

2.3 TEST SUBJECTS

2.3.1 Selection

The sixteen test subjects--chosen at random from the ranks of the United New York and United New Jersey Sandy Hook Pilots Benevolent Associations--are either presently working the Sandy Hook Channel or had previous experience in that area, and so are familiar with the channel and its characteristics.

2.3.2 Subject Preparation

Upon reporting to CAORF, subjects were briefed on the experiment and the manner in which it would be conducted. This briefing (see Appendix B) included an explanation of the ice and A/N conditions that would be encountered, the vessel's particulars, the navigational aids available, and the environmental conditions (lighting, visibility, wind and current) that would be imposed.

While most of the subjects were familiar with CAORF, and many with the particular vessel type used in the experiment, all were offered the opportunity to make a short familiarization run with the 80,000 DWT tanker.

2.3.3 Familiarization Run

The familiarization run gave the subjects a brief look at the vessel's maneuvering characteristics before they

participated in the actual experiment. The subjects were urged to make a few turns and maneuvers around six stationary vessels in a non-descript sea area. (See Figure 2-2.) The subject was not advised to follow any particular track and could terminate the run any time he felt familiar enough with the vessel and the visual display.

2.3.4 Watch Orders

Prior to commencing the experimental runs, each test subject was given a written set of watch orders to read for each run. The watch orders were identical except for the initial heading and direction of travel in the channel segment. Instructions on the use of the pre-nav displays were added to the watch orders for runs in the visual-with-precision-navigator-mode. Examples of all watch orders are in Appendix B.

2.4 SCENARIO DESIGN

Each of the sixteen test subjects was required to participate in two runs for each navigation mode. One run was made in the inbound direction and the other, outbound (see Table 2-1). Half the subjects in each mode made the inbound run first, while the remaining subjects made the outbound passage first.

2.4.1 Performance Measures

Five basic parameters were used to measure the performance of each subject: off-track deviation, course and helm orders, average angle of course correction, engine orders, and pilot workload. All performance measures relating to off-track deviation and distance off shoals and other objects were made relative to the vessel's center of gravity.

2.4.1.1 Off-Track Deviation

Deviations from the centerline or designated track of the channel, measured in feet right or left of the track, were recorded at 30-second intervals. Track plots for each run were made and used for an overview of general track-keeping ability and preciseness of navigation. Positions of the vessel were indicated at 90-second intervals throughout the entire course of the channel. Figures 2-3 and 2-4 show typical track plots for each navigation mode.

For analysis purposes, the channel was divided into three legs to be analyzed individually and in total for each run. The middle leg presented the greatest difficulty because it is the only segment with degraded conditions. Hence, the track plots exhibited better performance in both the entrance and exit legs of the channel. Since the indices of the off-track deviation will differ with respect to the reference track from which deviations are computed, more than one reference track was used in the analysis. These included the centerline of the channel and the mean track for all runs in the same direction.

Furthermore, for each reference track, average duration was computed as mean off-track deviation (signed); mean absolute value off-track deviation; and route mean square (RMS) off-track deviation. The closest point of approach (CPA) to shoals at the point of Sandy Hook was also used as a measure on the middle leg.

2.4.1.2 Course and Helm Orders

The course corrections made by the subject can be seen as a function of the number of course orders and rudder commands made during a run. These were recorded along with time-of-occurrence, position of vessel with reference to track and turnpoints of the

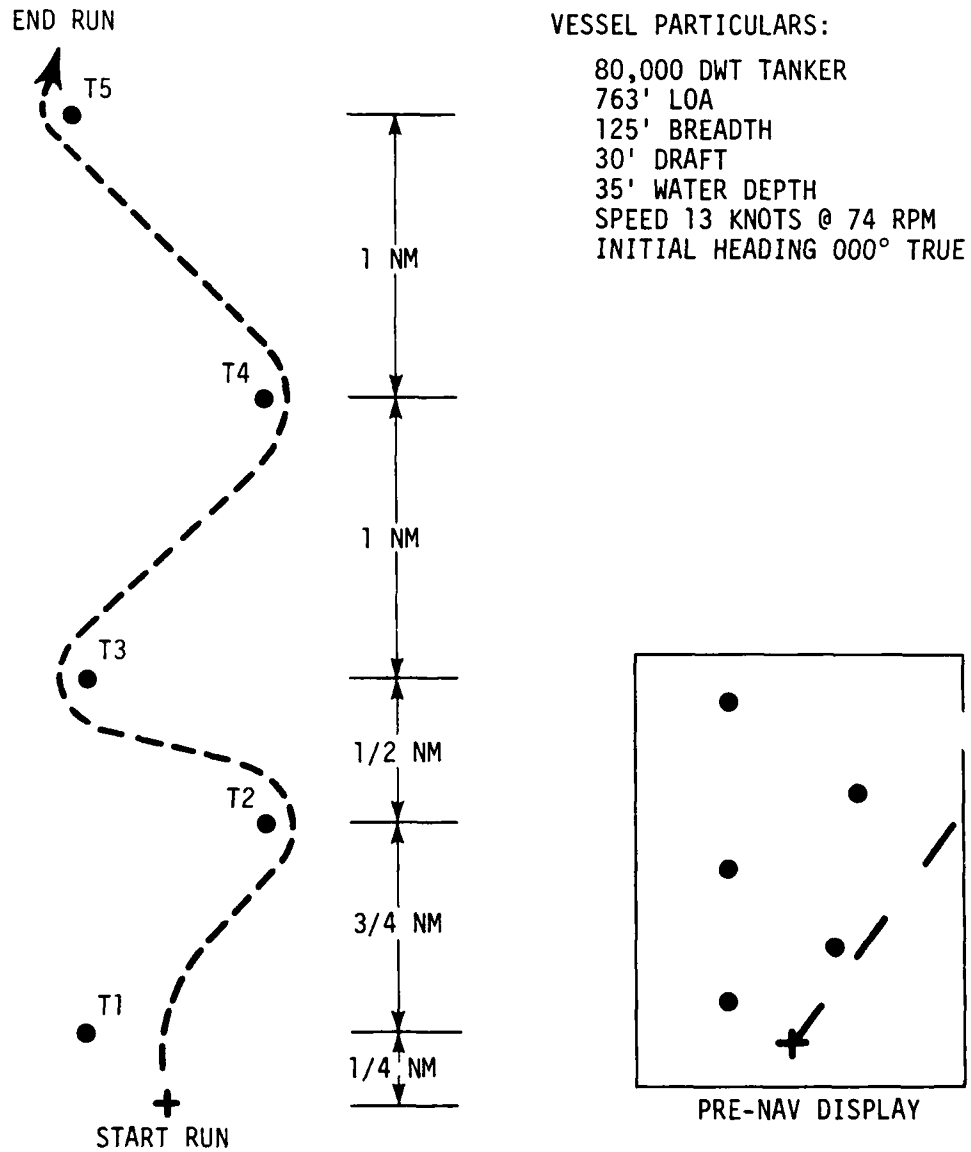

Figure 2-2. Familiarization Run

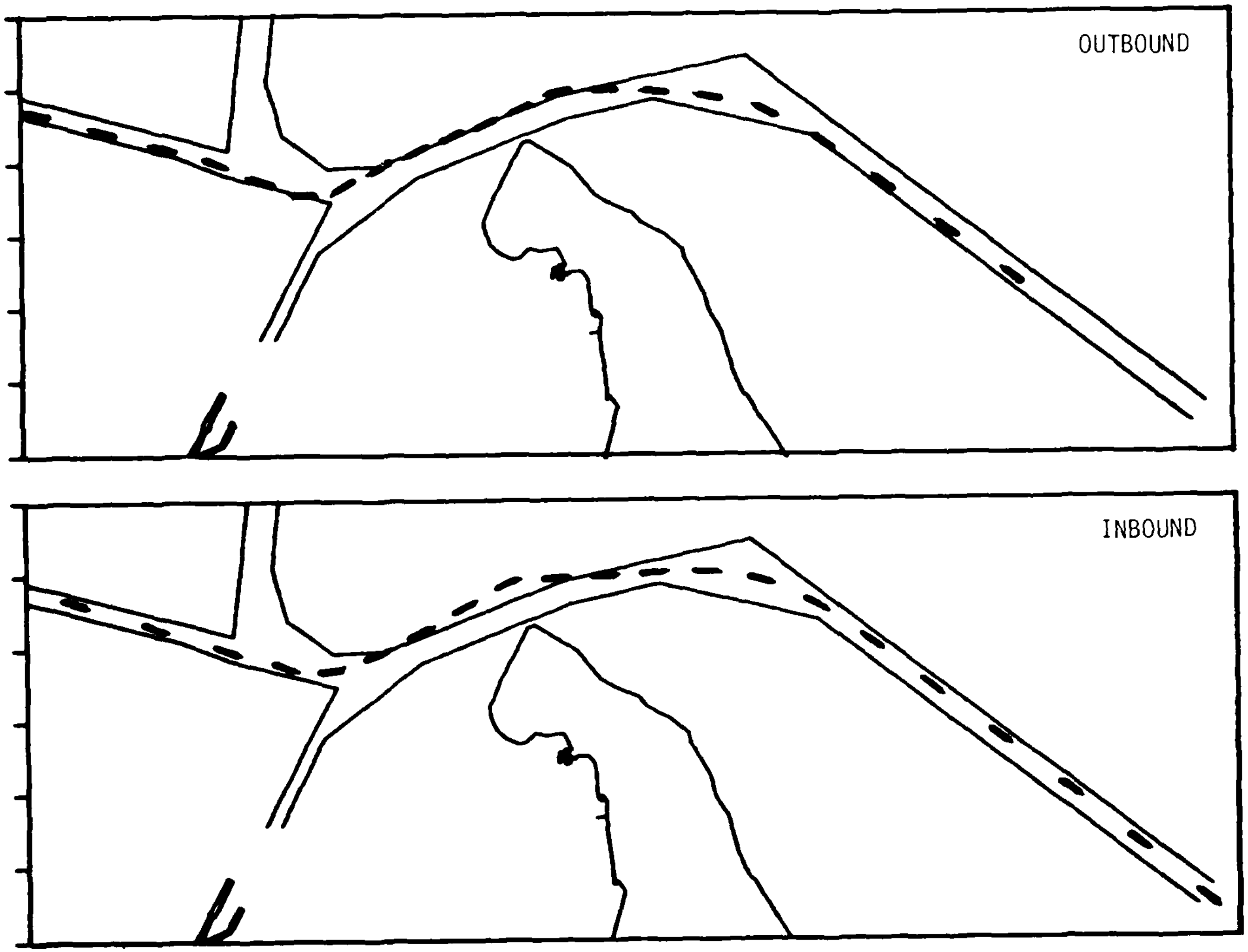

Figure 2-3. Typical Track Plots, Inbound and Outbound Runs, Visual-Only Mode

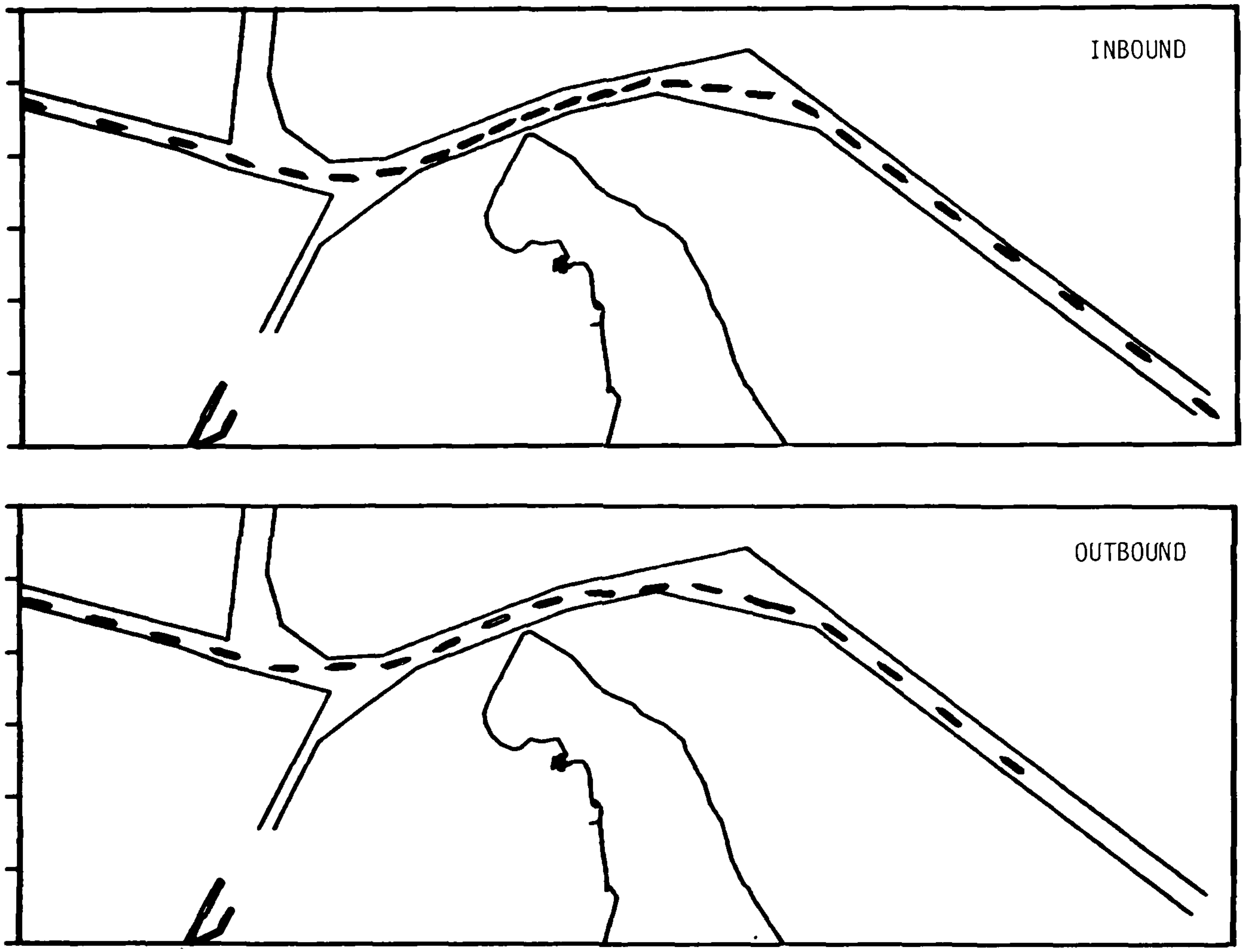

Figure 2-4. Typical Track Plots, Inbound and Outbound Runs, Visual-With-Precision-Navigator Mode

TABLE 2-1. SCENARIO DESIGN - SANDY HOOK
PRE-NAV EXPERIMENT

Navigation Mode	Subjects	Run 1	Run 2
Visual	S1	Inbound	Outbound
	S2	Inbound	Outbound
	S3	Inbound	Outbound
	S4	Inbound	Outbound
	S5	Outbound	Inbound
	S6	Outbound	Inbound
	S7	Outbound	Inbound
	S8	Outbound	Inbound
Pre-Nav	S9	Inbound	Outbound
	S10	Inbound	Outbound
	S11	Inbound	Outbound
	S12	Inbound	Outbound
	S13	Outbound	Inbound
	S14	Outbound	Inbound
	S15	Outbound	Inbound
	S16	Outbound	Inbound

channel, track velocity, and cross-track velocity. This course correction measure was expected to vary directly with the quantity of positional information available to the pilot and the speed with which this information can be assimilated.

2.4.1.3 Average Angle of Course Correction

From the records of course and helm orders compiled for each experimental run, an analysis was made to determine the average angle (and consequently, the magnitude) of correction made by the pilot. The hypothesis was that the rapid information flow available with the pre-nav would permit stricter adherence to the track than the slower, less accurate information flow typical of visual navigation. A stricter track maintenance would be possible only by continually correcting the vessel heading. The greater the number of corrections per time span, the smaller the magnitude of such corrections, since the vessel is moving away from the track for only a very short time before it is detected and adjusted.

2.4.1.4 Engine Orders

The number and nature of engine orders given during a transit, as well as their time of occurrence, were recorded to assess the relationship of speed to information flow. Precautionary behavior on the part of the pilot should, theoretically, manifest itself in a slower transit on visual-only runs, where the magnitude and accuracy of information received is substantially less than that using the precision navigator. Time-consuming, position-fixing methods warrant a more cautious

approach to the channel transit. It should be noted, however, that the necessity of maintaining control of the vessel in the presence of tidal currents which markedly affect vessel handling will limit or constrain the pilot's choice of a slower speed.

2.4.1.5 Pilot Workload

The human factors monitoring station at CAORF allows discreet observance and assessment of a test subject during an experiment. During this experiment each subject was observed and his physical activities, including chartwork, taking of bearings, and observation of instrumentation, were recorded under each of the two navigational modes.

2.4.2 Scenario Design

To fully evaluate the effectiveness of the precision navigator system, the Sandy Hook Channel was chosen for this experiment. A major segment of the channel is susceptible to extreme degradation of its buoy system each winter due to ice accumulation and movement, and is usually closed to navigation when these conditions exist. While the absence of buoys and radar precludes the use of most navigation aids, the realism of the scenario is maintained by presenting an extreme situation that is known to exist and has been experienced by many of the test subjects. Sandy Hook, therefore, is considered an appropriate locale for evaluating the precision navigator system.

The channel area used in this experiment was somewhat modified from the New York data base to show the land constituting Sandy Hook itself as ice and snow-covered, with ice accumulations at the point where the Hook extends into the ship channel.

The data base was further modified by removing some of the aids-to-navigation which normally mark the channel boundaries. The A/N configurations, which were degraded due to extreme ice conditions, are as follows:

- All buoys from the "10" buoy on the entrance leg, across the point of Sandy Hook to the "1" buoy on Raritan Bay East Reach inclusive, with the exception of the "15" (Schweers) buoy at the point of the Hook, are missing.

- All buoys marking the Leonardo Terminal Channel are missing.

- The Leonardo Range, the fixed lights on Sandy Hook and all buoys marking the channels and not listed above as missing are in position and are visible.

The tidal current element of the data base was derived from the Tidal Current Tables covering this area. The stage of the tide at the outset of each run was two hours before high water at the Battery at 1.5 knots flood current. The current set and drift throughout the entire location were updated automatically and simulated realistically in accordance with the local tide tables.

There were no wind effects present in any of the runs. The depth of water was maintained at a constant 10.67 meters (35 feet) in the channel, and shallow water effects were programmed according to the vessel's characteristics and the constant water depth.

Inbound runs commenced at the entrance buoys and were terminated by CAORF control station personnel when

the vessel was abeam the "6" buoy in Raritan Bay East Reach. All outbound runs commenced abeam the "10" buoy in Raritan Bay East Reach and were terminated when abeam the "4" buoy on the channel entrance leg. Subjects were advised that no vessel traffic would be encountered in the channel.

Refer to Appendix B, "Watch Orders," for the Sandy Hook Channel Segment showing the position of all aids-to-navigation that are missing due to the ice conditions.

CHAPTER 3

DISCUSSIONS AND RESULTS

3.1 SUMMARY OF FINDINGS

In keeping with the objectives of this study, it was found that the experiment results did contribute to a broader data base for the use of a pre-nav display type system in a narrow channel under conditions of extreme degradation of radar return and visual aids-to-navigation.

3.2 PILOT APPRAISAL OF PRENAV DISPLAYS

Test subjects stated that the analog display was preferred and easier to use than the digital readout. The reason given was its similarity to a radar display, familiarity with radar facilitating a more rapid assimilation of the information presented by the graphic display. However, many subjects noted that while the analog display was easier to use, the two displays should be used in conjunction since the digital readout gives useful, quantitative information which cannot be readily deduced from the analog display. The availability of this information reinforces information obtained from the analog. An example of this usefulness is the distance to turnpoint in nautical miles. While the vessel's position in relation to the turnpoint is graphically shown by the analog format, no idea of scale is adequately provided. This distance is given by the digital readout, however, and can be assimilated with the analog data for setting up turns, etc.

3.2.1 Priority of Digital Information

The information presented by the digital precision navigator display format is listed in descending order of importance to the pilot:

- o Feet across track, right or left.
- o Nautical miles to turnpoint.
- o Velocity across track right or left in feet/minutes.
- o Velocity along track in knots.

The cross-track error was found to be of primary importance to the subjects for determining position in the absence of key visual aids-to-navigation and radar.

The information next in importance, *distance* to the next turnpoint, assisted many subjects in determining where and when to initiate turns. Several subjects used visual sightings (buoys when still in position, fixed aids and ranges when available) to commence and complete turns. However, those subjects who were unable or did not attempt to establish any visual aids for negotiating turns, found the digital turnpoint and velocity-across-the-track information to be more readily obtained and assimilated using the analog display.

3.3 SAMPLE TRACKS

Typical results of channel transits made under the two different navigation modes are shown in Figures 3-1 and 3-2. Note that track maintenance ability was enhanced by use of the precision navigator. The visual-only runs typically exhibit poor recovery of the track after turning onto a new course

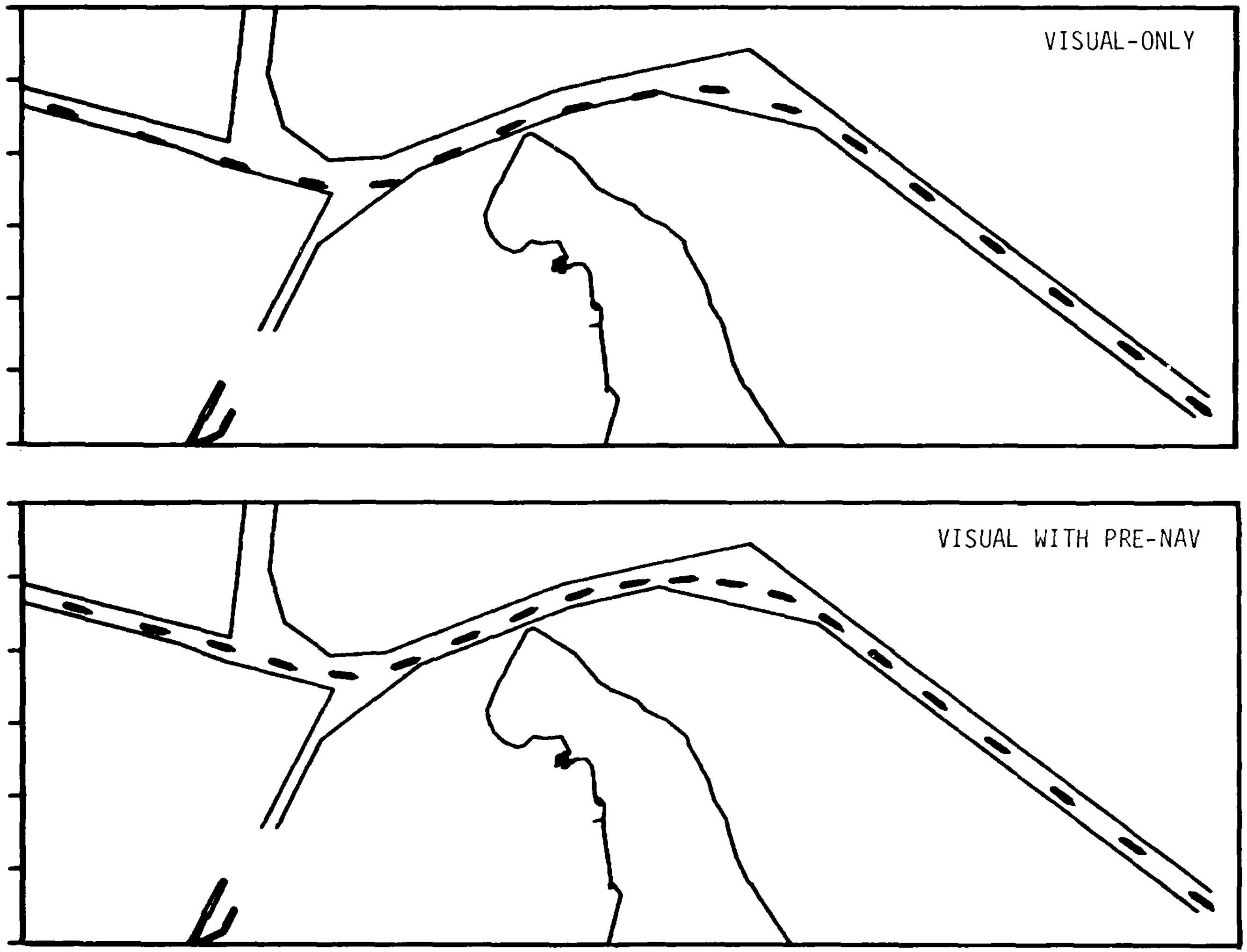

Figure 3-1. Typical Track Plots Inbound, Visual With Pre-Nav vs. Visual-Only Mode

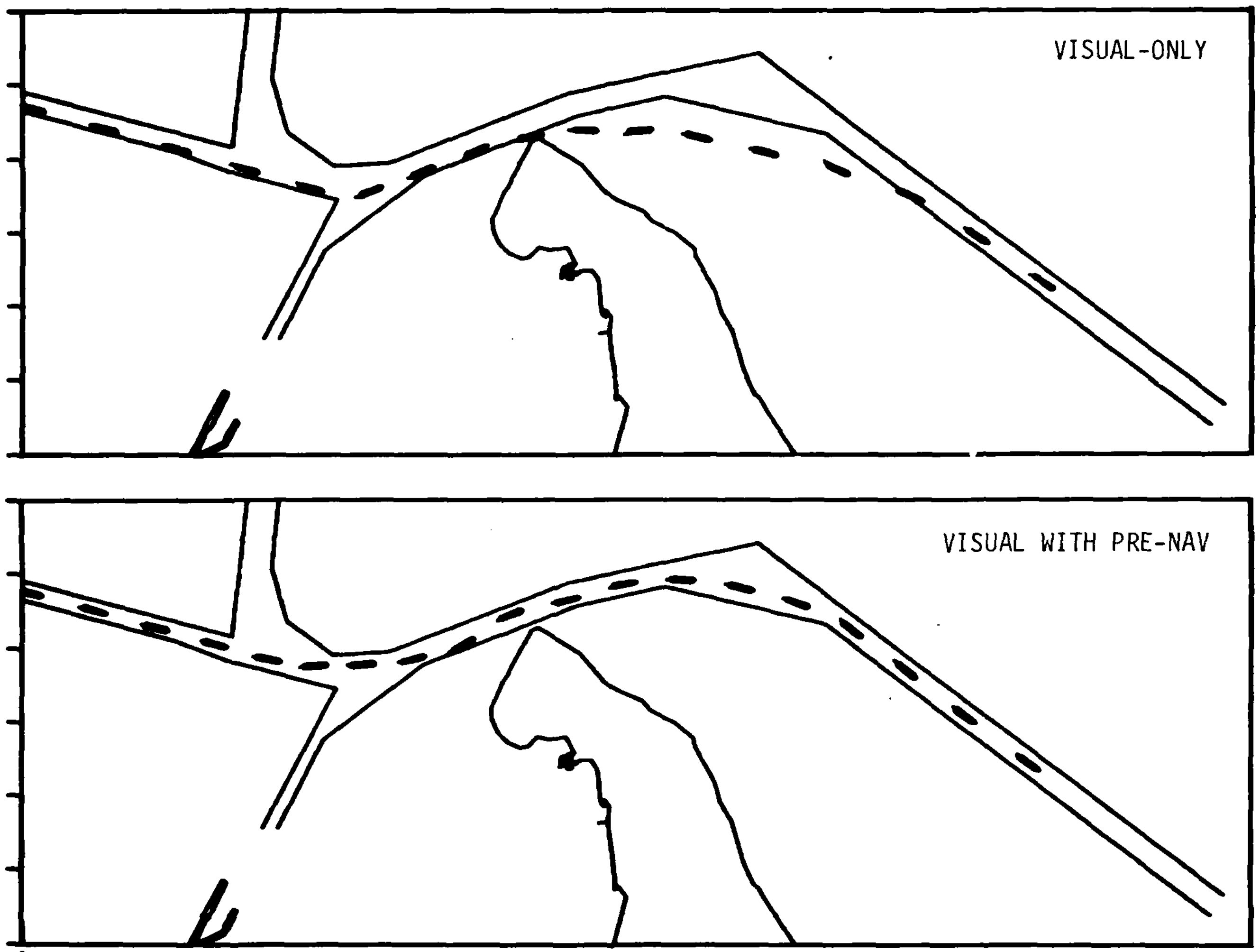

Figure 3-2. Typical Track Plots Outbound, Visual With Pre-Nav vs. Visual-Only Mode

leg. Time spent by the subject in confirming his position by visual bearings causes the vessel to overshoot the turn before a correction or pull-out can be initiated. Working with the pre-nav displays, however, permits accurate vessel handling since instantaneous feedback provides the information required to successfully complete turns and maintain position in the channel with minimum deviation. A complete set of track plots for all test subjects in each mode is presented in Appendixes C and D.

3.4 PILOT RECOMMENDATIONS FOR IMPROVED A/N CONFIGURATIONS

Pilot debriefing recommendations include improvements which could be made in the present aids-to-navigation configurations. These recommendations are suggested to improve safe navigation of the channel under conditions similar to those experienced during this experiment and are made in lieu of the availability of a precision navigator system. The recommendations are listed below according to the type of aid or improvement and in order of apparent importance to the pilots:

- Fixed Beacons: The use of beacons in place of present buoys was advocated by most subjects as a solution to loss of buoys during extreme ice conditions. The positions of the recommended beacons designate critical turns in the channel, i.e., the vicinity of the "10" buoy or "9" buoy junction with the Leonardo Channel. For the latter, beacon positions are recommended to replace one of the present buoys: "16," "17," "18," or the beacon could be positioned at the junction of the Leonardo Channel. A beacon and a higher intensity light is also advocated at the point of the Hook or where the present "15" (Schweers) buoy is located. Placement of these beacons should be carefully considered to prevent their loss at points where vessels are liable to hit them during wide swings when negotiating a turn.
- Ranges: Recommended for use on inbound passages primarily, ranges were suggested for the inbound 308 degree course and across the point of Sandy Hook leg or 245 degree course.
- Channel Widening: One subject recommended widening and dredging Sandy Hook Channel in the vicinity across Flynn's Knoll between the point of the Hook westward to the junction with Chapel Hill Channel.

3.5 NAVIGATION WITH VISUAL-ONLY AND PRECISION NAVIGATOR AIDS

Analysis of track-keeping performance exhibits a consistency among subjects in each navigation mode. Comparison between modes shows much improved performance by all subjects in the visual with precision navigator mode over the strictly visual mode. These findings substantiate earlier results of the Valdez [1] and MRIT [2] simulated groundings experiments.

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[1] W. McIlroy, Ph.D., "A Review of Valdez Experiment." First CAORF Symposium, Kings Point, New York, June 1977, pg. 105.

[2] H. Grossman, "Evaluation of a Marine Radar Interrogator/Transponder as a Navigation Aid in a Restricted Channel." Second CAORF Symposium, Kings Point, New York, Sept. 1978, Topic 4.

In the visual-only mode, data plots for runs showing vessel positions with reference to the track at 90-second intervals indicate that the subjects experienced a high degree of difficulty in safely navigating the channel under the severe conditions imposed. It was noted, however, that the test subjects were quick to develop alternate procedures for piloting in the absence of radar and the other key aids to navigation. Those subjects who made runs in the pre-nav mode were observed to be equally quick in adapting to the information format displayed and made good use of the displays in navigating the channel. The instantaneous display of positioning and prediction information available to the pilot with precision navigator eliminated the need for any other navigational methods for safe transit.

All the test subjects who used the precision navigator expressed satisfaction with the display system. While most of these subjects preferred to use the analog (graphic) display rather than the digital readout, many expressed the opinion that both formats should be used together to complement one another. Preference for the graphic display is in keeping with the MRIT study.

3.5.1 Visual-Only Mode

The conditions imposed in this scenario severely limited the availability of cues such as sighting of buoy pairs and landmass reference points. However, it was observed that the pilots developed different methods on short notice to overcome the lack of buoys and the unavailability of radar. The vast majority chose to use various ranges and/or bearings from the remaining buoys and fixed lights, thus relying solely on conventional position-determination methods. Some pilots used these methods to establish and maintain cross-track position, while others used the remaining A/N to establish lines of position (LOP) from which turns could be initiated or completed. An alternative procedure selected by one subject used length of time on a particular course leg with estimated speed along the track. All these methods, however, proved to be generally inexact and unreliable in determining cross-track position and time to initiate turns, and resulted in an undesirable level of performance. Due to unreliability of these methods approximately 80% of the visual-only runs were made with some departure from the recommended channel.

While not all channel departures resulted in groundings, the majority did. The number of groundings was a function of the degree of difficulty experienced by the subjects in navigating the middle leg of the channel where the degraded A/N conditions existed. Data plot analysis revealed that track-keeping performance was poorest in this section, while on the entrance and exit legs of the channel, ability to maintain the centerline was good because the normal aids were in position. Indications are that track-keeping abilities are adequate when visually navigating under normal conditions in good visibility and without the aid of radar.

These findings regarding poor track maintenance can be attributed to the time-consuming process of taking visual bearings and plotting lines of position. In addition, the accuracy of the resulting fix may be dubious due to the unavailability of strategically placed aids for effective cross bearings.

3.5.2 Visual With Precision Navigator Mode

Track-keeping performance in this mode of navigation is readily evidenced

by strict adherence to the centerline of the channel. Comparison of data plots for both visual and pre-nav runs indicates greatly improved performance with use of the precision navigator. With all other conditions and parameters remaining the same, this upgraded performance can be attributed to the information displays. Uniformity of the results among all the test subjects using the pre-nav rules out variability between subject capabilities as a contributing factor.

Ability of the pilots to not only maintain the vessel within channel boundaries, but to maintain position on the centerline or track without the aid of distance perception to land masses or navigational fixes indicates an almost total reliance on the precision navigator for positional information. The digital and analog formats gave precise and immediate indication of vessel position with respect to the track and turnpoints of the channel. Digital information, updated at 30-second intervals, and the analog display, updated continuously, allowed the subject to make course corrections at higher rates than in the visual mode. The recorded rudder/course order data supports this with a somewhat greater number of rudder and course orders being recorded on pre-nav runs. These runs show a markedly greater use of rudder orders over course orders in comparison to data recorded on visual-only runs. This latter finding appears to run contrary to anticipated results, bearing in mind that rate of turn during large course changes *is* best controlled through rudder orders. With the key words here being large course changes, we find course corrections made in the precision navigator mode to be small when compared to course changes made in the visual mode. A degree of personal preference by the pilot must have been part of his decision to use course or rudder orders. He may also have been influenced by some factor of the scenario or his opinion of the helmsmen's ability. (During most CAORF experiments, it has been observed that Master commands are often influenced by his helmsman's style of rudder use.)

When a test subject in the precision navigator mode did use course orders, it was found that the average magnitude of the course correction was less than the course orders given in the visual-only mode for the same channel segment.

Preliminary study of the rudder/course order data indicates that an inverse relationship exists between the magnitude of course corrections and the speed/accuracy of information flow. However, we can only concentrate on actual course orders at this point. Helm (rudder) orders do not fit into this relationship because rudder orders are used more to achieve a desired rate of change rather than a quantitative change. As indicated, however, the choice of course or rudder orders appears dependent upon individual pilot methodology. Hence, inclusion of helm orders in the evaluation of course correction can only come about when a satisfactory conversion scheme is developed to equate rudder orders to a specified angle of change. An attempt to develop such a scheme was made during the data analysis and the helm-course order relationship validated the effectiveness of all command data as a performance measure.

3.6 HUMAN FACTORS

From observations made at the unique CAORF human factors monitoring station, it was anticipated that a measurable distinction would be apparent in pilot activities and procedures when using the different modes of navigation. Indeed, tabulation of the subject's

physical activity on the bridge, and comparison of data between the two navigation modes showed a substantial difference in the level of activity.

In the visual with pre-nav mode, there was heavy reliance on the pre-nav equipment. The pilot took up a position in front of the displays and, in general, rarely moved from that position during the run except to occasionally glance at the chart. Conversely, subjects in the visual-only mode were quite active on the bridge. The degree of uncertainty in position-keeping necessitated constant reference to the chart and plotting of bearings, and both the pilot and mate made frequent use of the bridge wing peloruses. Such a high level of activity in the visual-only mode attests to pilot use of all possible information sources for navigating in this more demanding mode.

3.7 CONCLUSIONS

In the visual-only mode, pilot ability to safely navigate the channel under severely degraded conditions was extremely limited. The unacceptable level of performance which resulted was commented on by the test subjects during the post-run debriefing. Generally stated, their unanimous comments were that, with advance knowledge of such degraded conditions, the pilots would not normally attempt such a transit. It should be noted that this view was held by all the subjects, including those who had actually experienced similar conditions in real life.

The high number of channel departures which occurred in the visual-only mode substantiates the need for more and better information sources.

The precision navigator system proved to be a great improvement over visual methods of piloting and appears to confirm the results of the earlier MRIT and Valdez experiments. Information was readily assimilated and track-keeping ability was enhanced by the rapid, precise, informational format, enabling the test subjects to navigate safely and accurately, without the need to take time-consuming visual position fixes.

Post-run debriefings indicate a preference for the analog display over the digital due to its ease of assimilation. Most subjects did advise that both display formats be used together for optimum accuracy.

This study demonstrates a need for advanced informational display systems as navigation aids under less than optimum conditions. Although the practicality of this equipment has been shown, further experimentation may be necessary to determine levels of inaccuracy for complete pilot acceptance. Also, the most effective combination of display formats has yet to be designed and the economics of producing this display must be investigated before the equipment can be realistically proposed for shipboard use in restricted waters.

In addition, the study indicates a need for improved aids-to-navigation configurations in the Sandy Hook Channel. Bearing in mind that a compatible shipboard prototype of the equipment evaluated here may not come into general use for many years, we can, in the meantime, further evaluate the recommendations made here for interim aids such as beacons and ranges to permit the channel to remain open during severe ice conditions.

CHAPTER 4

DATA ANALYSIS

4.1 EXPERIMENTAL DESIGN AND ANALYSIS: TECHNICAL DESCRIPTION

For purposes of statistical analysis, the independent variables of this experiment were arranged as a 2 x 2 Latin square with two between-square variables (see Table 4-1). The variables of the basic Latin square were: run sequence (inbound-outbound); run number in the sequence (first run, second run); and direction of transit (inbound, outbound). Navigation mode (visual, pre-nav) was treated as a between-subjects, between-square variable. Leg of the channel was treated as a within-subjects, between-square variable. The analysis of variance appropriate to this design is given in Table 4-2. This analysis provides statistical tests for the following variables of interest: Are there differences in test-subject performance between or among the levels of each independent variable, i.e., visual versus pre-nav, inbound versus outbound? These overall differences are assessed by the main effect of each

TABLE 4-1. EXPERIMENT DESIGN

Navigation Mode	Sequence	Test Subject	Run 1 (Leg 1 Leg 2 Leg 3)	Run 2 (Leg 1 Leg 2 Leg 3)
Visual	1	1	Inbound	Outbound
		2	Inbound	Outbound
		3	Inbound	Outbound
		4	Inbound	Outbound
	2	5	Outbound	Inbound
		6	Outbound	Inbound
		7	Outbound	Inbound
		8	Outbound	Inbound
Pre-Nav	1	9	Inbound	Outbound
		10	Inbound	Outbound
		11	Inbound	Outbound
		12	Inbound	Outbound
	2	13	Outbound	Inbound
		14	Outbound	Inbound
		15	Outbound	Inbound
		16	Outbound	Inbound

independent variable. In addition to the main effect tests, the analysis evaluates the interaction between navigation mode and leg of channel. Interactions among the Latin square variables are, by definition, confounded and are not assessed.

4.2 TRACK-KEEPING PERFORMANCE

Data pertaining to the vessel's track-keeping performance within the channel were subjected to statistical analysis. The resulting interactions and main effects are herein discussed.

4.2.1 Off-Track Deviation

The evidence of improved pilot performance of test subjects using the precision navigator (see Figures 3-1 and 3-2, and Appendixes C and D) is

TABLE 4-2. LATIN SQUARE ANALYSIS OF VARIANCE SOURCE TABLE

	Source of Variation	Degrees of Freedom	Description of Effect
1.	Navigation mode (A)	1	Main effect for nav mode
2[a].	Run sequence (B)	1	Main effect for run sequence
3[a].	A x B	1	Interaction of nav mode and run sequence
4.	Between-subjects error	12	Error term for testing 1, 2 and 3
5.	Direction of transit (C)	1	Main effect for direction of transit
6.	Run number (D)	1	Main effect for run number
7.	A x C	1	Interaction of nav mode and direction
8.	A x D	1	Interaction of nav mode and run number
9.	Within-subjects error_1	12	Error term for text 5, 6, 7, and 8
10.	Leg of channel (E)	2	Main effect for leg of the channel
11.	A x E	2	Interaction of nav mode and leg
12[a].	B x E	2	Interaction of sequence and leg
13[a].	A x B x E	2	Interaction of nav mode, sequence, and leg
14.	Within-subjects error_2	24	Error term for testing 10, 11, 12, and 13

TABLE 4-2. LATIN SQUARE ANALYSIS OF VARIANCE SOURCE TABLE (CONT)

Source of Variation	Degrees of Freedom	Description of Effect
15. C x E	[illegible]	Interaction of direction and leg
16. D x E	[illegible]	Interaction of run number and leg
17. A x C x E	[illegible]	Interaction of nav mode, direction and leg
18. A x D x E	2	Interaction of nav mode, run number, and leg
19. Within-subjects $error_3$	24	Error term for testing 15, 16, 17, and 18
Total	95	

[a] Since these effects are essentially uninterpretable, they are not discussed in the text. They were included in the analysis as control variables and to reduce error (unexplained) variance.

supported by the analysis of variance. (See Tables 4-3 and 4-4 for ANOVA and mean values of RMS off-track deviation.) The resultant significant effect for navigation mode was anticipated and proved to be particularly pronounced in Leg 2 (see Figure 4-1) which contains all the aid-to-navigation discrepancies and both channel turns. However, an interesting interaction of navigation mode and run number (see Figure 4-2) was revealed in the visual-only mode, which exhibits to some extent the adaptability of the pilot. (See Table 4-5.) Subjects in this mode attained significantly smaller deviations in their second run [$t(12) = 3.33$, $p < 0.01$], attesting to a learning effect which was apparent in this mode only. Off-track deviations actually increased slightly on the second run of subjects who used the pre-nav displays; but the difference in performance between the navigation modes for their second runs remains significant in Leg 2 where pre-nav mode deviations were significantly below those in visual-only (see Figure 4-3).

The data also indicates a consistency in off-track deviations in the exit leg regardless of direction of transit or navigation mode. While Leg 2 displayed the highest deviations, comparisons of Legs 1 and 3--in which all aids to navigation remained unaffected by the severe ice conditions simulated--reveal that the exit leg (Leg 3 inbound, Leg 1 outbound) always exhibited a higher deviation than the entrance leg. The explanation here appears to be, in general, an inattentiveness to precise navigation or a shift to the visual mode since the worst (meaning Leg 2) was over, and the run

TABLE 4-3. PERFORMANCE MEASURE: RMS OFF-TRACK DEVIATION - CENTERLINE (NM)

Latin Square Analysis of Variance Source Table

Source	df	Mean Square	F	Probability
Navigation mode (A)	1	0.00840	24.427	0.001
Sequence (B)	1	0.00014	0.410	ns
A x B	1	0.00001	0.032	ns
Between-subjects error	12	0.00034	--	--
Direction (C)	1	0.00003	0.007	ns
Run number (D)	1	0.00161	4.100	0.07
A x C	1	0.00024	0.607	ns
A x D	1	0.00283	7.199	0.02
Within-subjects $error_1$	12	0.00039	--	--
Leg (E)	2	0.01240	61.014	0.001
A x E	2	0.00200	9.831	0.003
B x E	2	0.00091	4.500	0.04
A x B x E	2	0.00126	6.193	0.02
Within-subjects $error_2$	24	0.00020	--	--
C x E	2	0.00066	1.921	ns
D x E	2	0.00020	0.580	ns
A x C x E	2	0.00052	1.517	ns
A x D x E	2	0.00011	0.312	ns
Within-subjects $error_3$	24	0.00034	--	--
Total	95			

TABLE 4-4. PERFORMANCE MEASURE: RMS OFF-TRACK DEVIATION - CENTERLINE (FEET)

Table of Means

	Inbound	Outbound	Mean	Run 1	Run 2
Visual	226	247	237	294	180
Pre-Nav	133	116	124	117	133
Mean	180	182		205	156

	Inbound			Outbound		
	Leg 1	Leg 2	Leg 3	Leg 1	Leg 2	Leg 3
Visual	84	382	213	155	469	118
Pre-Nav	78	224	97	88	190	71
Mean	81	303	155	121	330	94

	Run 1			Run 2		
	Leg 1	Leg 2	Leg 3	Leg 1	Leg 2	Leg 3
Visual	158	512	212	82	339	118
Pre-Nav	69	203	78	97	211	89
Mean	113	358	145	89	275	104

	Leg 1	Leg 2	Leg 3	Mean
Visual	120	426	165	237
Pre-Nav	83	207	84	124
Mean	101	316	124	

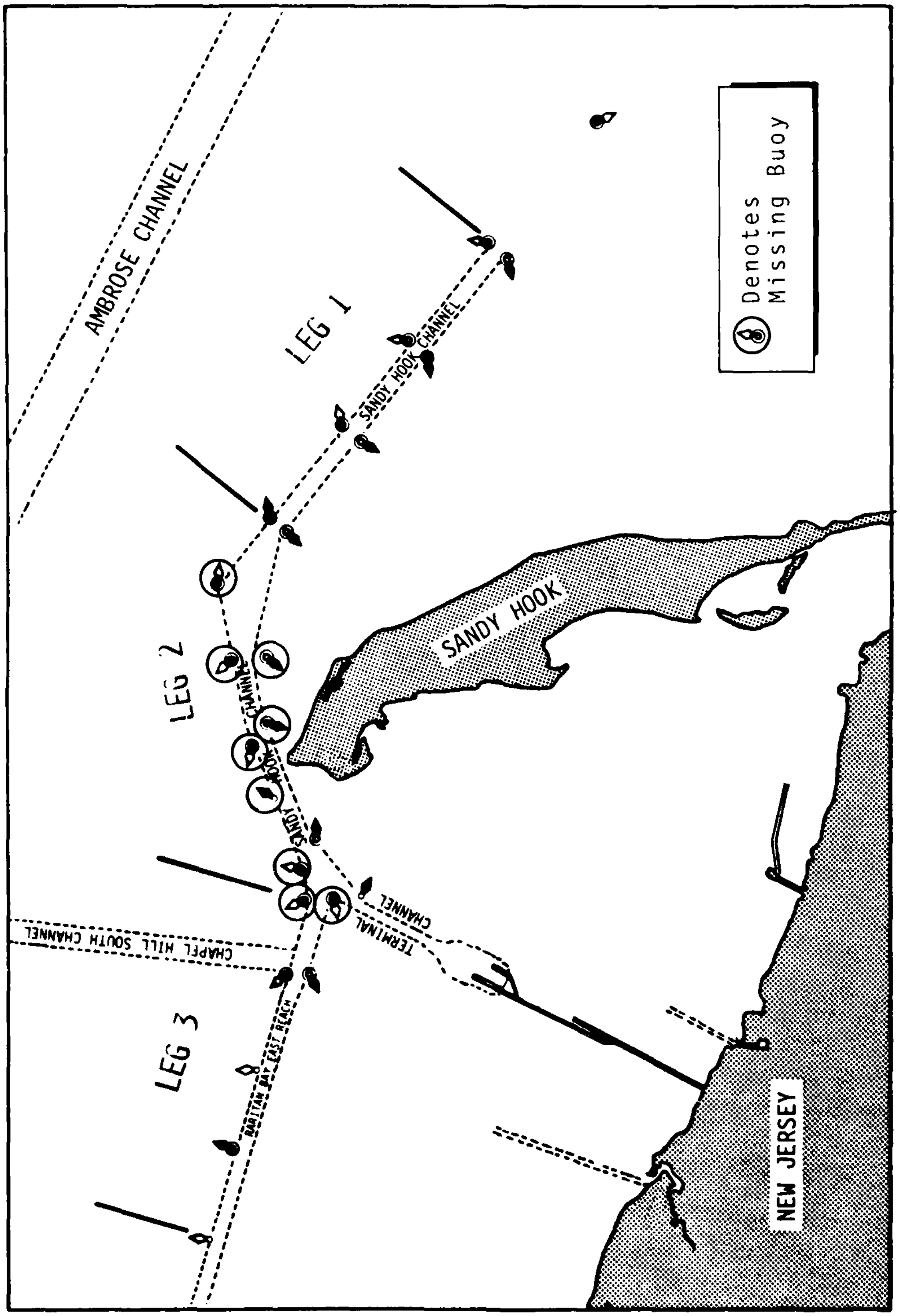

Figure 4-1. Nautical Chart

TABLE 4-5. NON-ORTHOGONAL CONTRAST ANALYSIS OF THE INTERACTION OF NAVIGATION MODE AND CHANNEL LEG FOR RMS OFF-TRACK (CENTERLINE) DEVIATIONS

	Experimental Condition							
	Visual			Pre-Nav				
Contrast	Leg 1	Leg 2	Leg 3	Leg 1	Leg 2	Leg 3	Computed F[a]	Description of the Contrast
1	+1/2	0	+1/2	-1/2	0	-1/2	6.19*	Compares performance in legs 1 and 3 of the visual-only condition to legs 1 and 3 of the pre-nav condition.
2	0	+1	0	0	-1	0	42.48**	Compares performance in leg 2 of visual-only runs to leg 2 of the pre-nav runs.
3	+1/2	-1	+1/2	0	0	0	117.08**	Compares performance in leg 2 to legs 1 and 3 for the visual-only conditions.
4	0	0	0	+1/2	-1	+1/2	22.33**	Compares performance in leg 2 to legs 1 and 3 for the pre-nav conditions.

[a] As a conservative test, each F is evaluated with 1 and 12 degrees of freedom.
*$p < 0.03$
**$p < 0.001$

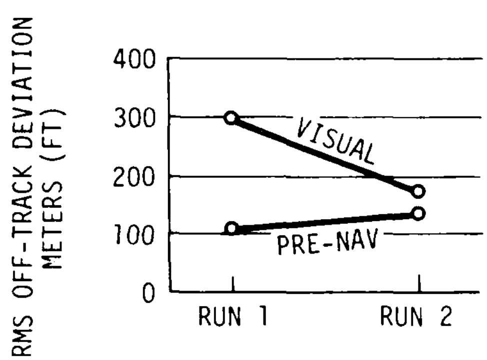

Figure 4-2. Interaction of Navigation Mode and Run Number on RMS Off-Track Deviation

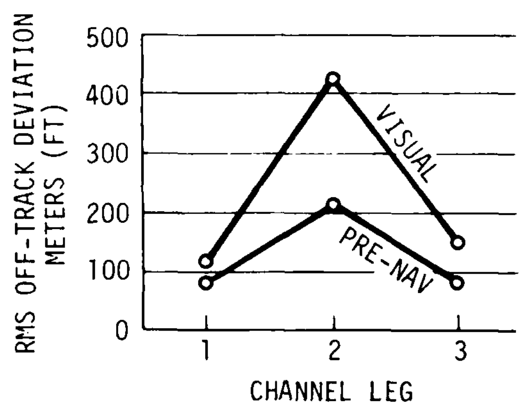

Figure 4-3. Interaction of Navigation Mode and Channel Leg on RMS Off-Track Deviation

was nearly complete. This was observed in all cases where the pilot engaged in casual conversation with the mate, and conning of the vessel was quite easy, requiring maintenance of a straight course through the remaining well-marked leg. Furthermore, more precise navigation was observed on the entrance leg where the subject was concerned with the vessel's alignment prior to initiating the first turn.

4.2.2 Frequency of Zero Crossings

The analysis of variance performed for this measure exhibits a higher frequency of zero (centerline) crossings in the pre-nav mode (see Tables 4-6 and 4-7). This attests to the more precise track-keeping possible with the precision navigator displays. Obviously, the closer the vessel path is to the channel centerline, the more the vessel is likely to cross the centerline. Leg 2 of the channel exhibited the highest frequency of crossings in both modes, but the preciseness of track-keeping does not help to explain the number of zero crossings on this leg in the visual mode. The differences observed between channel legs is probably due more to the setting for and recovery from turns included in Leg 2. Regardless of the mode, navigation in this leg presupposes more erratic track-keeping because of the presence of turns than in either of the other two legs, where a straight-line track is easily maintained. This, therefore, resulted in additional centerline crossings.

A finding which corresponds to the apparent pilot inattentiveness in the exit leg mentioned previously with regard to off-track deviation, is that zero crossings are more numerous in the entrance leg than in the exit leg, regardless of direction of transit or navigation mode. (See Figure 4-4.)

4.2.3 Off-Track Velocity

A significant main effect for the channel leg ($F(2,24)=68.63$, $p < 0.001$) was obtained in the analysis of RMS off-track velocity due to a significantly

TABLE 4-6. PERFORMANCE MEASURE: FREQUENCY OF ZERO (CENTERLINE) CROSSINGS

Latin Square Analysis of Variance Source Table

Source	df	Mean Square	F	Probability
Navigation mode (A)	1	9.2327	12.689	0.004
Sequence (B)	1	0.1482	0.203	ns
A x B	1	0.6291	0.861	ns
Between-subjects error	12	0.7305	--	--
Direction (C)	1	0.0005	0.0003	ns
Run number (D)	1	0.0517	0.029	ns
A x C	1	5.8863	3.239	0.10
A x D	1	0.0517	0.029	ns
Within-subjects $error_1$	12	1.8174	--	--
Leg (E)	2	13.2169	11.985	0.001
A x E	2	2.5407	2.304	0.12
B x E	2	0.1312	0.119	ns
A x B x E	2	1.9478	1.766	ns
Within-subjects $error_2$	24	1.1028	--	--
C x E	2	11.0496	6.813	0.005
D x E	2	2.5830	1.593	ns
A x C x E	2	0.4355	0.269	ns
A x D x E	2	0.0830	0.051	ns
Within-subjects $error_3$	24	1.6219	--	--
Total	95			

TABLE 4-7. PERFORMANCE MEASURE: FREQUENCY OF ZERO (CENTERLINE) CROSSINGS

Table of Means

	Inbound	Outbound	Mean	Run 1	Run 2
Visual	1.8	1.3	1.5	1.5	1.5
Pre-Nav	1.9	2.4	2.2	2.2	2.1
Mean	1.9	1.8		1.9	1.8

	Inbound			Outbound		
	Leg 1	Leg 2	Leg 3	Leg 1	Leg 2	Leg 3
Visual	2.3	2.3	0.9	0.8	1.9	1.3
Pre-Nav	2.0	2.8	1.0	1.0	3.5	2.8
Mean	2.1	2.5	0.9	0.9	2.7	2.0

	Run 1			Run 2		
	Leg 1	Leg 2	Leg 3	Leg 1	Leg 2	Leg 3
Visual	1.5	2.4	0.8	1.5	1.8	1.4
Pre-Nav	1.6	3.4	1.6	1.3	2.9	2.1
Mean	1.6	2.9	1.2	1.4	2.3	1.8

	Leg 1	Leg 2	Leg 3	Mean
Visual	1.5	2.1	1.1	1.5
Pre-Nav	1.5	3.1	1.9	2.2
Mean	1.5	2.6	1.5	

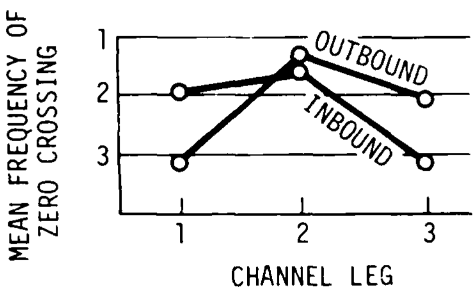

Figure 4-4. Interaction of Direction of Transit and Channel Leg on Frequency of Zero Crossings

higher mean off-track velocity in the second leg of the channel than in either Legs 1 or 3. (See Tables 4-8 and 4-9.) Once again, this effect may be attributable to the channel turns in Leg 2. The higher off-track velocities resulted from the subject's failure to quickly detect and control the vessel's lateral motion which, at best, is difficult to accomplish when turning the vessel and relatively simple to accomplish when traveling a straight, well-marked channel leg. Other interactions and effects for off-track velocity proved to be insignificant and no relationship to navigation mode could be developed from the data.

4.2.4 Ship Speed Through The Water

No effects for average speed as a function of navigation mode were revealed in the analysis of variance. Effects of direction of transit and run number were evident, but were significant for channel Legs 1 and 2 only. Average speed was significantly higher for outbound than for inbound runs in both pre-nav and visual modes. (See Tables 4-10 and 4-11.)

A learning effect is indicated where, for the first and second channel legs, the average speed was significantly higher for the subjects' second runs than for their initial runs ($F(1,12)=9.07$, $p < 0.01$).

The lack of any effects for speed related to the navigation mode would indicate that use of the pre-nav displays allowed the subject to navigate more accurately, but not necessarily more productively. Speed varied across legs of the channel in the following manner: average speed was significantly lower in the second leg than either Legs 1 or 3 and was somewhat lower in Leg 3 than in Leg 1. (See Figure 4-5.) In Leg 2, which was almost totally devoid of navigational aids, the subjects showed caution by reducing RPM. This action left more RPM available to assist steering (by "kicking" the stern around) when an extra bit of control might be needed during difficult turns.

Leg 1 exhibited the highest average speed because the accuracy of navigation which could be attained is the highest in this leg, regardless of navigation mode. The higher speed exhibited is a direct result of the subject's confidence in transiting this part of the channel, which was well-marked by gated buoys.

4.2.5 Frequency of Groundings

Consistent with the findings regarding off-track deviations, the number of runs which resulted in a grounding was significantly higher for the visual-only condition (10 out of 16), than for the pre-nav condition (1 out of 16; x (1)= 11.221, $p < 0.001$). Within the visual-only condition, groundings were slightly more frequent for the inbound runs (6 of 8) than for the outbound runs (4 of 8). Also, consistent with the off-track

TABLE 4-8. PERFORMANCE MEASURE: RMS OFF-TRACK (CENTERLINE) VELOCITY

Latin Square Analysis of Variance Source Table

Source	df	Mean Square	F	Probability
Navigation mode (A)	1	0.0177	0.074	ns
Sequence (B)	1	0.1044	0.438	ns
A x B	1	0.1613	0.676	ns
Between-subjects error	12	0.2386	--	--
Direction (C)	1	0.0173	0.189	ns
Run number (D)	1	0.0091	0.100	ns
A x C	1	0.0156	0.171	ns
A x D	1	0.6678	7.296	0.02
Within-subjects $error_1$	12	0.0915	--	--
Leg (E)	2	12.4524	68.632	0.001
A x E	2	0.0200	0.110	ns
B x E	2	0.0124	0.068	ns
A x B x E	2	0.5155	2.841	0.08
Within-subjects $error_2$	24	0.1814	--	--
C x E	2	0.4295	2.873	0.08
D x E	2	0.0157	0.105	ns
A x C x E	2	0.0990	0.662	ns
A x D x E	2	0.0145	0.097	ns
Within-subjects $error_3$	24	0.1495	--	--
Total	95			

TABLE 4-9. PERFORMANCE MEASURE: RMS OFF-TRACK VELOCITY

Table of Means

	Inbound	Outbound	Mean	Run 1	Run 2
Visual	0.94	0.88	0.91	0.98	0.84
Pre-Nav	0.88	0.88	0.88	0.79	0.98
Mean	0.91	0.88		0.89	0.91

	Inbound			Outbound		
	Leg 1	Leg 2	Leg 3	Leg 1	Leg 2	Leg 3
Visual	0.54	1.74	0.52	0.68	1.54	0.43
Pre-Nav	0.47	1.77	0.41	0.64	1.40	0.60
Mean	0.50	1.76	0.47	0.66	1.47	0.52

	Run 1			Run 2		
	Leg 1	Leg 2	Leg 3	Leg 1	Leg 2	Leg 3
Visual	0.71	1.69	0.56	0.51	1.60	0.40
Pre-Nav	0.43	1.48	0.46	0.66	1.70	0.56
Mean	0.57	1.58	0.51	0.59	1.65	0.48

	Leg 1	Leg 2	Leg 3	Mean
Visual	0.61	1.64	0.48	0.91
Pre-Nav	0.55	1.59	0.51	0.88
Mean	0.58	1.61	0.49	

TABLE 4-10. PERFORMANCE MEASURE: AVERAGE SPEED THROUGH THE WATER

Latin Square Analysis of Variance Source Table

Source	df	Mean Square	F	Probability
Navigation mode (A)	1	0.170	0.027	ns
Sequence (B)	1	18.945	3.055	0.11
A x B	1	0.022	0.004	ns
Between-subjects error	12	6.201	--	--
Direction (C)	1	9.485	10.563	0.007
Run number (D)	1	8.144	9.070	0.01
A x C	1	2.224	2.477	0.14
A x D	1	1.550	1.726	ns
Within-subjects error_1	12	0.898	--	--
Leg (E)	2	52.641	33.795	0.001
A x E	2	0.777	0.499	ns
B x E	2	0.689	0.442	ns
A x B x E	2	1.922	1.234	ns
Within-subjects error_2	24	1.558	--	--
C x E	2	8.599	8.479	0.002
D x E	2	5.050	4.979	0.02
A x C x E	2	0.693	0.682	ns
A x D x E	2	0.213	0.210	ns
Within-subjects error_3	24	1.014	--	--
Total	95			

TABLE 4-11. PERFORMANCE MEASURE: AVERAGE SPEED THROUGH THE WATER

Table of Means

	Inbound	Outbound	Mean	Run 1	Run 2
Visual	11.0	11.9	11.5	11.3	11.6
Pre-Nav	11.2	11.5	11.4	11.0	11.8
Mean	11.1	11.7		11.1	11.7

	Inbound			Outbound		
	Leg 1	Leg 2	Leg 3	Leg 1	Leg 2	Leg 3
Visual	11.8	9.3	11.8	13.4	10.8	11.6
Pre-Nav	11.6	9.8	12.3	13.0	10.0	11.6
Mean	11.7	9.5	12.1	13.2	10.4	11.6

	Run 1			Run 2		
	Leg 1	Leg 2	Leg 3	Leg 1	Leg 2	Leg 3
Visual	12.2	9.8	11.9	13.0	10.4	11.5
Pre-Nav	11.6	9.2	12.1	12.9	10.6	11.8
Mean	11.9	9.5	12.0	13.0	10.5	11.7

	Leg 1	Leg 2	Leg 3	Mean
Visual	12.6	10.1	11.7	11.5
Pre-Nav	12.3	9.9	12.0	11.4
Mean	12.5	9.9	11.8	

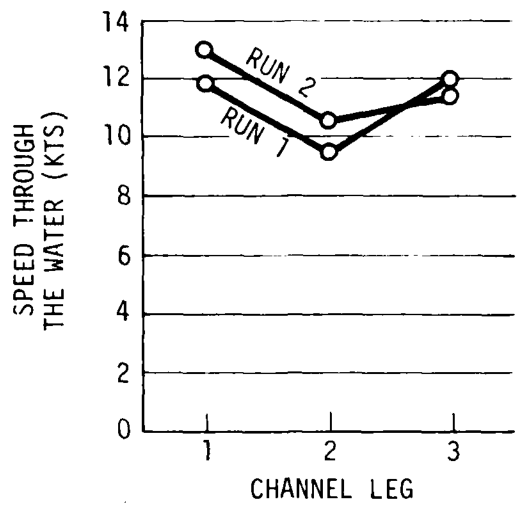

Figure 4-5. Interaction of Run Number and Channel Leg on Speed Through the Water

deviation measure, the relative frequency of groundings between the first and second runs of subjects in the visual-only condition demonstrates improvement through practice: 7 or 8 initial runs resulted in grounding; whereas grounding occurrred in only 3 of the 8 second runs (p=0.10 by a Fisher's Exact Probability Test).

4.2.6 Swept Path Analysis

In order to provide a graphic presentation of the relative performances of track-keeping between each group (visual and pre-nav), the tracks were combined with eight tracks on one plot displaying the ship profiles at very close time intervals. This results in a dark band of the swept path of each vessel. The pilots have been combined as follows with eight tracks on each:

- o Visual inbound, Figure 4-6
- o Visual outbound, Figure 4-7
- o Pre-nav inbound, Figure 4-8
- o Pre-nav outbound, Figure 4-9

In considering the swept path in Leg 2, it is clearly apparent in both visual inbound and outbound that the spread is great, and often extends outside the channel boundaries (see Figure 4-10, same scale as Figures 4-6 through 4-9).

It can also be seen that track-keeping in the visual mode is accomplished with a fair amount of accuracy in Leg 1 except for one diversion outbound. This is assisted by the gated buoys in Leg 1. Leg 3, on the other hand, exhibits somewhat less accuracy as seen by a slightly wider spread of paths. The spread is similar in both inbound and outbound visual runs with the exception of one diversion in the inbound run. The explanation for the difference in the spread of swept paths between Leg 1 and Leg 3 appears to be in the poorer arrangement of buoys in Leg 3. Whereas, in Leg 1, gated buoys mark the entire leg, thereby significantly aiding visual navigation and track-keeping performance, buoyage in Leg 3 is limited to marking the north side of the channel only. Both the fact that the spread of swept paths is only slightly wider in Leg 3 than in Leg 1 and the low number of diversions from the channel found in Leg 3 in the visual mode attest to the well-developed range-estimating abilities of the pilots when presented with sufficient visual aids.

Examination of the pre-nav mode swept path plots presents a much improved performance picture in Leg 2 when compared to the wide spreads found in the visual mode. Little improvement can be seen in first leg performance over visual piloting and a slight improvement is noticeable in Leg 3 with a narrower swept path spread in either direction of transit. The much improved performance in Leg 2 utilizing

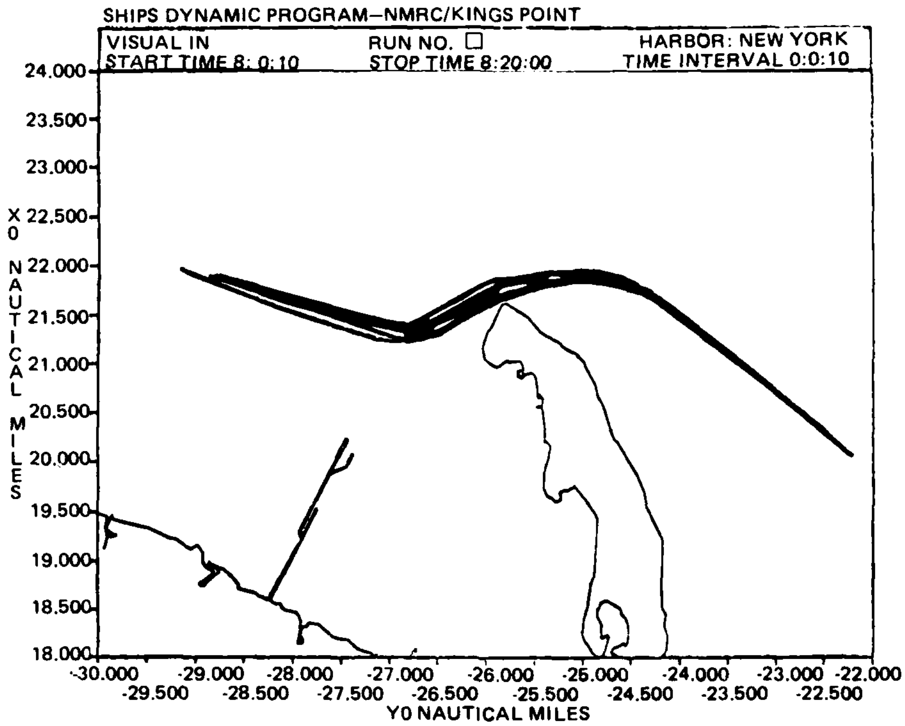

Figure 4-6. Combined Track Plot, Visual Inbound

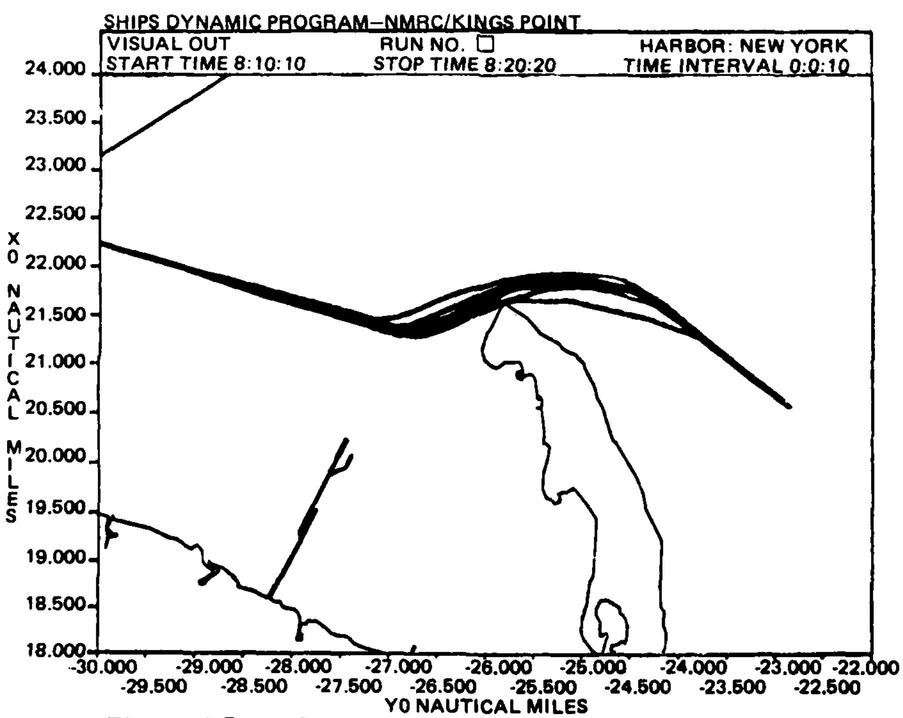

Figure 4-7. Combined Track Plot, Visual Outbound

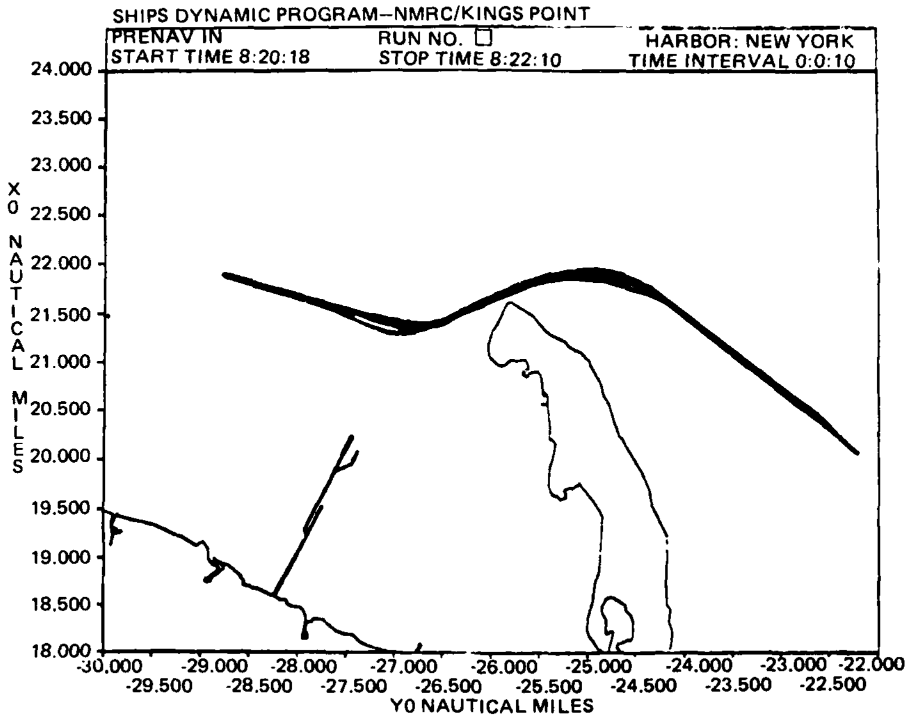

Figure 4-8. Combined Track Plot, Pre-Nav Inbound

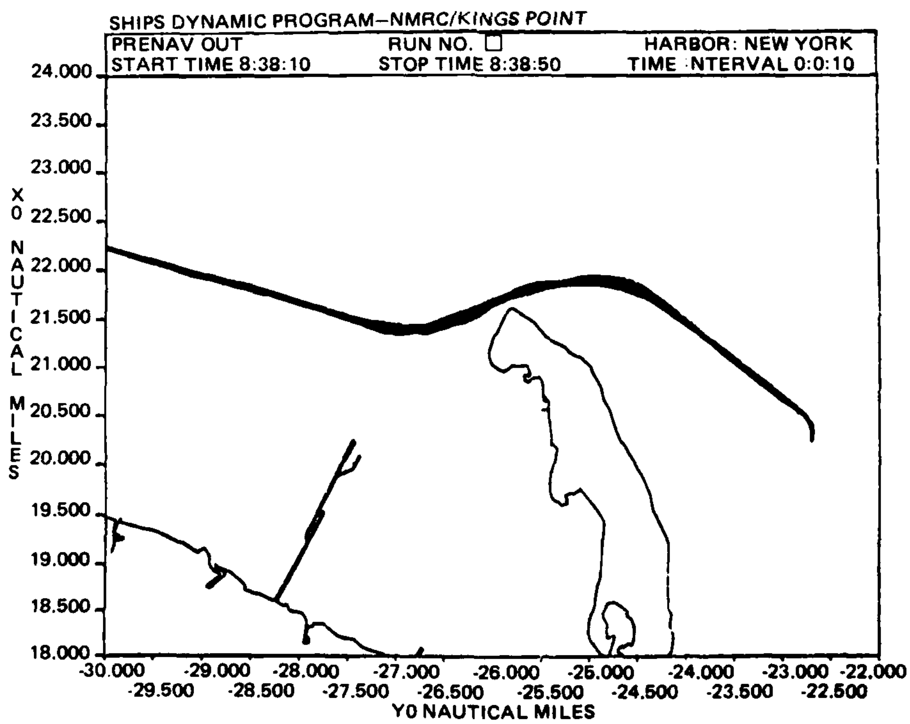

Figure 4-9. Combined Track Plot, Pre-Nav Outbound

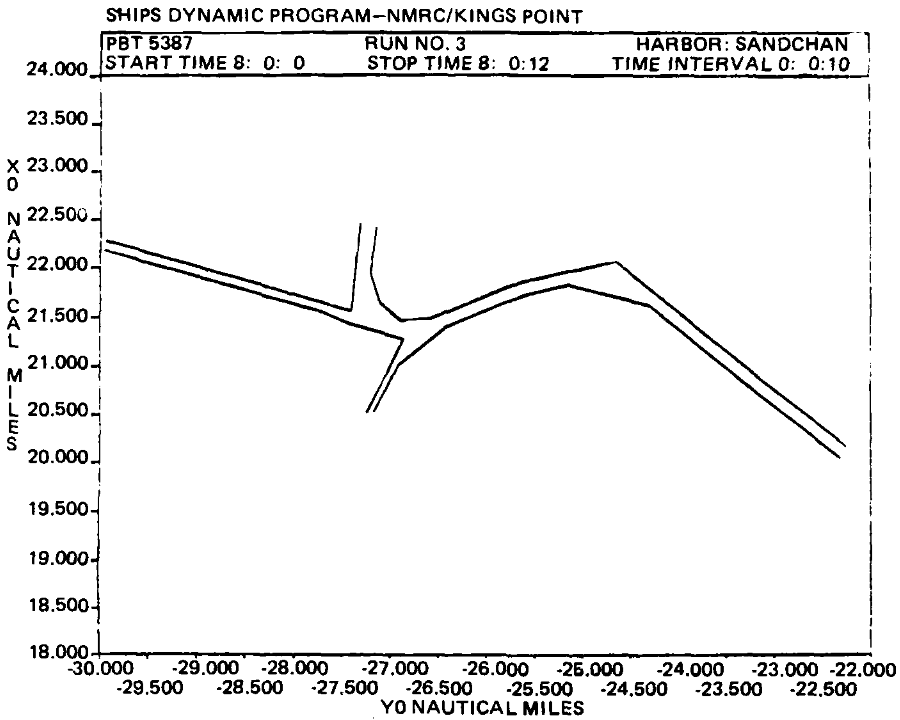

Figure 4-10. Sandy Hook Channel Boundaries

the precision navigator displays is marred only by some minor bulges in the swept path envelopes. For the most part these occur only at the times where, due to the nature of the vessel and her sluggish handling characteristics, a more accurate maintenance of the track-line through the turn is not to be expected. Widening of the channel in the vicinity of the turns such as cut-off corners, etc. (Figure 4-10) also contributed to the less accurate track maintenance which resulted in these bulges. The subjects made use of these wider turn areas to line up for the next course as the turn was completed. The unexpectedly high off-track deviations noted in Leg 2 despite the use of the pre-nav (see Table 4-4) are due to inclusion in Leg 2 of both turns for analysis purposes. These results are somewhat misleading without reference to the plots, especially in the pre-nav mode inbound where the narrow envelope of swept path between the turns is most evident. Bulges noted along Leg 2 in the outbound pre-nav mode may be due to steadying up difficulties encountered when the distance between the turns is so short that it does not allow some pilots sufficient time to regain the track line before setting up for the next turn.

4.3 BRIDGE HELM AND ENGINE ORDERS

The frequency and magnitude of rudder, course, and engine orders were compiled from data recorded at the human factors monitoring station and by the mate on the CAORF bridge. These data were analyzed according to the design presented in Tables 4-1 and 4-2 with the following modification: Due to the relatively low frequency of bridge orders issued in the first and third legs of the channel, the data for these two legs were combined as the first level, and Leg 2 as the second level of the factor. As in the analysis

of track-keeping performance, the effects which were statistically significant in the analysis of variance are described for each command measure. For cases of significant interactions among the experimental factors, a summary of the findings of appropriate pair comparisons is provided.

4.3.1 Number Of Rudder/Course Commands

One significant effect for the number of rudder commands was revealed by *the analysis shown in Table 4-12.* It was found that rudder commands were predominant in the second leg as opposed to Legs 1 and 3 (see Table 4-13). Course commands, when analyzed for variance (see Table 4-14), revealed a main effect for run number with a reduction in the number of course commands given on the subjects' second runs. Moreover, this reduction was *more pronounced in* Leg 2 *than in* Legs 1 and 3 (see Table 4-15). A ratio or rudder-to-course-commands analysis (see Table 4-16) exhibited significantly more rudder-to-course-commands given in Leg 2 than in Legs 1 and 3, and in the second run relative to the first run. These efforts are independent of the navigation mode and indicate that a learning effect takes place, with subjects *reverting to more* rudder commands in lieu of course commands on their second run. The subjects apparently found that, in Leg 2, direct rudder orders were more effective in making turns and in maintaining the channel centerline in the absence of buoys. In the straight, well-marked Legs 1 and 3, commands were nearly equally divided between rudder and course commands. (See Table 4-17.)

The use of more rudder commands than course commands, especially in a channel segment where it may take longer to detect off-track deviation and, therefore, longer to correct it, may be attributable to a method of control wherein the pilot decides the rate at which the correction is made. Use of a course order leaves to the helmsman's discretion how much rudder is to be used. This method may be employed by the pilot in both visual and pre-nav modes because the ship-type utilized in the experiment is characterized by relatively slow response to helm and engine orders.

4.3.2 Average Angle of Rudder Commands

A significant interaction involving direction of transit and channel leg was obtained in the analysis of variance of this measure. (See Tables 4-18 and 4-19.) A Newman-Keuls comparison of the interaction means indicates that *the average rudder command was* significantly larger (p @ 0.01) for the second leg of the channel relative to the first and third legs in the inbound transits. This difference was negligible for outbound runs. A marginal three-way interaction of navigation mode, direction of transit, and channel leg suggests that this effect was limited to the runs made in the visual mode. That is, for visual runs, the average angle of rudder commands was significantly larger for Leg 2 than for Legs 1 and 3 of the inbound runs. No significant differences in average angle of rudder commands were observed for the runs in the pre-nav mode. This indicates that the accuracy of the information provided by the pre-nav system promotes shiphandling behavior which requires lessrudder angle to maintain a course and, therefore, allows maximum available rudder angle in the event that an unusual maneuver is necessary.

TABLE 4-12. PERFORMANCE MEASURE: NUMBER OF RUDDER COMMANDS

Latin Square Analysis of Variance Source Table

Source	df	Mean Square	F	Probability
Navigation mode (A)	1	83.266	0.747	ns
Sequence (B)	1	1.266	0.011	ns
A x B	1	141.016	1.265	ns
Between-subjects error	12	111.484	--	--
Direction (C)	1	40.641	2.563	ns
Run number (D)	1	17.016	1.073	ns
A x C	1	0.016	0.001	ns
A x D	1	26.266	1.656	ns
Within-subjects $error_1$	12	15.859	--	--
Leg (E)	1	1859.766	59.226	$p < 0.001$
A x E	1	23.766	0.757	ns
B x E	1	0.141	0.005	ns
A x B x E	1	0.766	0.024	ns
Within-subjects $error_2$	12	31.401	--	--
C x E	1	1.891	0.112	ns
D x E	1	0.766	0.046	ns
A x C x E	1	13.141	0.781	ns
A x D x E	1	2.641	0.157	ns
Within-subjects $error_3$	12	16.817	--	--
Total	63			

TABLE 4-13. PERFORMANCE MEASURE: NUMBER OF RUDDER COMMANDS

Table of Means					
	Inbound	Outbound	Run 1	Run 2	Mean
Visual	8.88	10.50	9.81	9.56	9.69
Pre-Nav	11.19	12.75	10.81	13.13	11.97
Mean	10.03	11.63	10.31	11.34	

	Inbound		Outbound	
	Legs 1 & 3	Leg 2	Legs 1 & 3	Leg 2
Visual	3.50	14.25	3.88	17.13
Pre-Nav	6.13	16.25	8.25	17.25
Mean	4.81	15.25	6.06	17.19

	Run 1		Run 2	
	Legs 1 & 3	Leg 2	Legs 1 & 3	Leg 2
Visual	3.50	16.13	3.88	15.25
Pre-Nav	6.13	15.50	8.25	18.00
Mean	4.81	15.81	6.06	16.63

	Legs 1 & 3	Leg 2	Mean
Visual	3.69	15.69	9.69
Pre-Nav	7.19	16.75	11.97
Mean	5.44	16.22	

TABLE 4-14. PERFORMANCE MEASURE: NUMBER OF COURSE COMMANDS

Latin Square Analysis of Variance Source Table

Source	df	Mean Square	F	Probability
Navigation mode (A)	1	12.250	0.459	ns
Sequence (B)	1	25.000	0.938	ns
A x B	1	36.000	1.350	ns
Between-subjects error	12	26.667	--	--
Direction (C)	1	12.250	1.105	ns
Run number (D)	1	64.000	5.774	$p < 0.05$
A x C	1	2.250	0.203	ns
A x D	1	9.000	0.812	ns
Within-subjects error_1	12	11.083	--	--
Leg (E)	1	1.000	0.049	ns
A x E	1	49.000	2.405	ns
B x E	1	1.000	0.049	ns
A x B x E	1	4.000	0.196	ns
Within-subjects error_2	12	20.375	--	--
C x E	1	9.000	3.130	ns
D x E	1	25.000	8.696	$p < 0.025$
A x C x E	1	1.000	0.348	ns
A x D x E	1	9.000	3.130	ns
Within-subjects error_3	12	2.875	--	--
Total	63			

TABLE 4-15. PERFORMANCE MEASURE: NUMBER OF COURSE COMMANDS

Table of Means

	Inbound	Outbound	Run 1	Run 2	Mean
Visual	7.63	7.13	8.00	6.75	7.38
Pre-Nav	7.13	5.88	7.88	5.13	6.50
Mean	7.38	6.50	7.94	5.94	

	Inbound		Outbound	
	Legs 1 & 3	Leg 2	Legs 1 & 3	Leg 2
Visual	7.13	8.13	6.13	8.13
Pre-Nav	8.63	5.63	6.38	5.38
Mean	7.88	6.88	6.25	6.75

	Run 1		Run 2	
	Legs 1 & 3	Leg 2	Legs 1 & 3	Leg 2
Visual	6.25	9.75	7.00	6.50
Pre-Nav	8.63	7.13	6.38	3.88
Mean	7.44	8.44	6.69	5.19

	Legs 1 & 3	Leg 2	Mean
Visual	6.63	8.13	7.38
Pre-Nav	7.50	5.50	6.50
Mean	7.06	6.81	

TABLE 4-16. PERFORMANCE MEASURE: RATIO OF RUDDER TO COURSE COMMANDS

Latin Square Analysis of Variance Source Table

Source	df	Mean Square	F	Probability
Navigation mode (A)	1	13.388	1.036	ns
Sequence (B)	1	11.911	0.891	ns
A x B	1	31.458	2.353	ns
Between-subjects error	12	13.371	--	--
Direction (C)	1	4.332	1.025	ns
Run number (D)	1	24.047	5.688	$p < 0.05$
A x C	1	1.132	0.268	ns
A x D	1	2.234	0.526	ns
Within-subjects error_1	12	4.228	--	--
Leg (E)	1	113.715	9.536	$p < 0.01$
A x E	1	2.963	0.248	ns
B x E	1	15.652	1.313	ns
A x B x E	1	15.990	1.341	ns
Within-subjects error_2	12	11.925	--	--
C x E	1	0.061	0.019	ns
D x E	1	15.435	4.712	$p < 0.10$
A x C x E	1	0.553	0.170	ns
A x D x E	1	0.0007	0.0002	ns
Within-subjects error_3	12	3.262	--	--
Total	63			

TABLE 4-17. PERFORMANCE MEASURE: RATIO OF RUDDER TO COURSE COMMANDS

Table of Means

	Inbound	Outbound	Run 1	Run 2	Mean
Visual	1.64	1.90	1.34	2.20	1.77
Pre-Nav	2.31	3.09	1.90	3.50	2.70
Mean	1.98	2.50	1.63	2.85	

	Inbound		Outbound	
	Legs 1 & 3	Leg 2	Legs 1 & 3	Leg 2
Visual	0.46	2.82	0.84	2.95
Pre-Nav	0.88	3.73	1.42	4.77
Mean	0.67	3.28	1.13	3.86

	Run 1		Run 2	
	Legs 1 & 3	Leg 2	Legs 1 & 3	Leg 2
Visual	0.72	1.97	0.59	3.81
Pre-Nav	0.84	2.96	1.47	5.54
Mean	0.78	2.47	1.03	4.67

	Legs 1 & 3	Leg 2	Mean
Visual	0.65	2.89	1.77
Pre-Nav	1.15	4.25	2.70
Mean	0.90	3.57	

TABLE 4-18. PERFORMANCE MEASURE: AVERAGE ANGLE OF RUDDER COMMANDS

Latin Square Analysis of Variance Source Table

Source	df	Mean Square	F	Probability
Navigation mode (A)	1	4.693	0.147	ns
Sequence (B)	1	48.424	1.512	ns
A x B	1	174.868	5.460	$p < 0.05$
Between-subjects error	12	32.028	--	--
Direction (C)	1	22.717	1.179	ns
Run number (D)	1	31.523	1.636	ns
A x C	1	0.437	0.023	ns
A x D	1	26.227	1.361	ns
Within-subjects $error_1$	12	19.276	--	--
Leg (E)	1	79.410	3.510	$p < 0.01$
A x E	1	2.492	0.110	ns
B x E	1	91.705	4.053	$p < 0.10$
A x B x E	1	6.573	0.291	ns
Within-subjects $error_2$	12	22.624	--	--
C x E	1	69.035	5.905	$p < 0.05$
D x E	1	26.150	2.237	ns
A x C x E	1	54.631	4.673	$p < 0.10$
A x D x E	1	4.479	0.383	ns
Within-subjects $error_3$	12	11.691	--	--
Total	63			

TABLE 4-19. PERFORMANCE MEASURE: AVERAGE ANGLE OF RUDDER COMMANDS

Table of Means

	Inbound	Outbound	Run 1	Run 2	Mean
Visual	13.916	12.890	13.465	13.341	13.403
Pre-Nav	13.540	12.183	14.204	11.519	12.862
Mean	13.728	12.537	13.834	12.430	

	Inbound		Outbound	
	Legs 1 & 3	Leg 2	Legs 1 & 3	Leg 2
Visual	10.643_a	17.190_b	13.541_a	12.239_a
Pre-Nav	23.509_a	14.571_a	11.381_a	12.985_a
Mean	11.576_a	15.881_a	12.461_a	12.612_a

	Run 1		Run 2	
	Legs 1 & 3	Leg 2	Legs 1 & 3	Leg 2
Visual	11.250	15.680	12.934	13.749
Pre-Nav	12.913	15.495	10.978	12.061
Mean	12.081	15.588	11.956	12.905

	Legs 1 & 3	Leg 2	Mean
Visual	12.092	14.714	13.403
Pre-Nav	11.945	13.778	12.862
Mean	12.081	14.246	

4.3.3 Average Angle Between Consecutive Course Commands

A number of significant interrelated effects emerged in the analysis of variance for this performance measure. (See Tables 4-20 and 4-21.) These effects can be summarized as follows: the average angle between consecutive course commands was consistently larger for Leg 2 than for Legs 1 and 3 in all but the inbound/pre-nav runs. From analysis of the rudder command data, it was noted that the use of rudder commands was prevalent in the second leg of the channel. When course orders were used in the second leg during visual mode runs, the increase in changes was due to greater deviation from the track line. This was a result of the subjects' longer detection latencies to lateral deviation from intended track.

4.3.4 Number of Engine Orders

The analysis of variance for this measure indicates one significant effect. It was found that engine orders were more numerous in the first of the two runs made by subjects. (See Table 4-22 and 4-23.) The learning effect with regard to engine order changes was apparently independent of navigation mode, indicating the rapid adaptability of the pilots to channel conditions.

TABLE 4-20. PERFORMANCE MEASURE: AVERAGE ANGLE BETWEEN CONSECUTIVE COURSE COMMANDS

Latin Square Analysis of Variance Source Table

Source	df	Mean Square	F	Probability
Navigation mode (A)	1	1.164	0.114	ns
Sequence (B)	1	11.894	1.169	ns
A x B	1	4.714	0.463	ns
Between-subjects error	12	10.176	--	--
Direction (C)	1	4.780	1.609	ns
Run number (D)	1	0.047	0.016	ns
A x C	1	9.978	3.360	$p < 0.10$
A x D	1	6.294	2.119	ns
Within-subjects error_1	12	2.970	--	--
Leg (E)	1	36.618	7.327	$p < 0.025$
A x E	1	0.013	0.003	ns
B x E	1	17.317	3.465	$p < 0.10$
A x B x E	1	0.147	0.030	ns
Within-subjects error_2	12	4.998	--	--
C x E	1	19.173	5.191	$p < 0.05$
D x E	1	1.584	0.429	ns
A x C x E	1	12.189	3.300	$p < 0.10$
A x D x E	1	4.671	1.265	ns
Within-subjects error_3	12	3.694	--	--
Total	63			

TABLE 4-21. PERFORMANCE MEASURE: AVERAGE ANGLE BETWEEN CONSECUTIVE COURSE COMMANDS

Table of Means

	Inbound	Outbound	Run 1	Run 2	Mean
Visual	3.03	2.78	3.19	2.62	2.90
Pre-Nav	1.97	3.30	2.29	2.97	2.63
Mean	2.50	3.04	2.74	2.80	

	Inbound		Outbound	
	Legs 1 & 3	Leg 2	Legs 1 & 3	Leg 2
Visual	2.39	3.66	1.93	3.64
Pre-Nav	2.18	1.75	1.55	5.06
Mean	2.29	2.70	1.74	4.35

	Run 1		Run 2	
	Legs 1 & 3	Leg 2	Legs 1 & 3	Leg 2
Visual	2.34	4.05	1.99	3.25
Pre-Nav	1.95	2.64	1.78	4.17
Mean	2.14	3.34	1.88	3.71

	Legs 1 & 3	Leg 2	Mean
Visual	2.16	3.65	2.90
Pre-Nav	1.86	3.40	2.63
Mean	2.01	3.53	

TABLE 4-22. PERFORMANCE MEASURE: NUMBER OF SPEED/RPM COMMANDS

Latin Square Analysis of Variance Source Table

Source	df	Mean Square	F	Probability
Navigation mode (A)	1	0.016	0.002	ns
Sequence (B)	1	43.891	4.780	$p < 0.05$
A x B	1	0.391	0.043	ns
Between-subjects error	12	9.182	--	--
Direction (C)	1	4.516	2.718	ns
Run number (D)	1	11.391	6.856	$p < 0.025$
A x C	1	0.016	0.009	ns
A x D	1	1.891	1.138	ns
Within-subjects error_1	12	1.611	--	-
Leg (E)	1	5.641	2.009	ns
A x E	1	1.266	0.451	ns
B x E	1	17.016	6.061	$p < 0.05$
A x B x E	1	0.141	0.050	ns
Within-subjects error_2	12	2.807	--	--
C x E	1	2.641	1.767	ns
D x E	1	0.016	0.011	ns
A x C x E	1	0.016	0.011	ns
A x D x E	1	0.141	0.091	ns
Within-subjects error_3	12	1.495	--	--
Total	63			

TABLE 4-23. PERFORMANCE MEASURE: NUMBER OF SPEED/RPM COMMANDS

Table of Means					
	Inbound	Outbound	Run 1	Run 2	Mean
Visual	2.63	2.13	2.63	2.13	2.38
Pre-Nav	2.63	2.06	2.94	1.74	2.34
Mean	2.63	2.09	2.78	1.94	

	Inbound		Outbound	
	Legs 1 & 3	Leg 2	Legs 1 & 3	Leg 2
Visual	2.00	3.25	1.88	2.38
Pre-Nav	2.25	3.00	2.13	2.00
Mean	2.13	3.13	2.00	2.19

	Run 1		Run 2	
	Legs 1 & 3	Leg 2	Legs 1 & 3	Leg 2
Visual	2.25	3.00	1.63	2.63
Pre-Nav	2.75	3.13	1.63	1.88
Mean	2.50	3.06	1.63	2.25

	Legs 1 & 3	Leg 2	Mean
Visual	1.94	2.81	2.38
Pre-Nav	2.19	2.50	2.34
Mean	2.06	2.66	

APPENDIX A

THE COMPUTER AIDED OPERATIONS RESEARCH FACILITY (CAORF)

A.1 DESCRIPTION OF CAORF

CAORF is the sophisticated ship-maneuvering simulator operated by the U.S. Maritime Administration for controlled research into man-ship-environment problems. Controlled experiments, which might require several vessels, cannot be performed readily in the real world and would certainly be ruled out for testing situations that involve potential danger. Such experiments can be performed safely and easily at CAORF. A simplified cutaway of the simulator building is shown in Figure A-1 and the relationships among the major subsystems are illustrated in Figure A-2.

All actions called for by the watch officer on the bridge are fed through a central computer that alters the visual scene and all bridge displays and repeaters in accordance with the calculated dynamic response of ownship and the environmental situation being simulated. CAORF has the capability of simulating any ship, port, or area in the world. The major subsystems are:

- **Wheelhouse,** which contains all equipment and controls needed by the test subject watch officer to maneuver ownship through a scenario, including propulsion and steering controls, navigational equipment and communication gear.

- **Central Data Processor,** which computes the motion of ownship in accordance with its known characteristics, models the behavior of all other traffic ships, and drives the appropriate bridge indicators.

- **Image Generator,** which constructs the computer-generated visual image of the surrounding environment and traffic ships that is projected onto a cylindrical screen for visual realism.

- **Radar Signal Generator,** which synthesizes video signals to stimulate the bridge radars and collision avoidance system for the display of traffic ships and surrounding environment.

- **Control Station,** from which the experiment is started and stopped, traffic ships and environment can be controlled, mechanical failures can be introduced, and external communications with ownship's bridge can be simulated.

- **Human Factors Monitoring Station,** from which unobtrusive observation and video recording of test subject behavior can be carried out by experimental psychologists.

A.2 SIMULATED BRIDGE

The simulated bridge consists of a wheelhouse 20 feet (6.1 m) wide and 14 feet (4.3 m) deep. The equipment on the CAORF bridge is similar to that normally available in the merchant fleet and responds with realistically duplicated time delays and accuracy. The arrangement is based on contemporary bridge design and includes the following equipment:

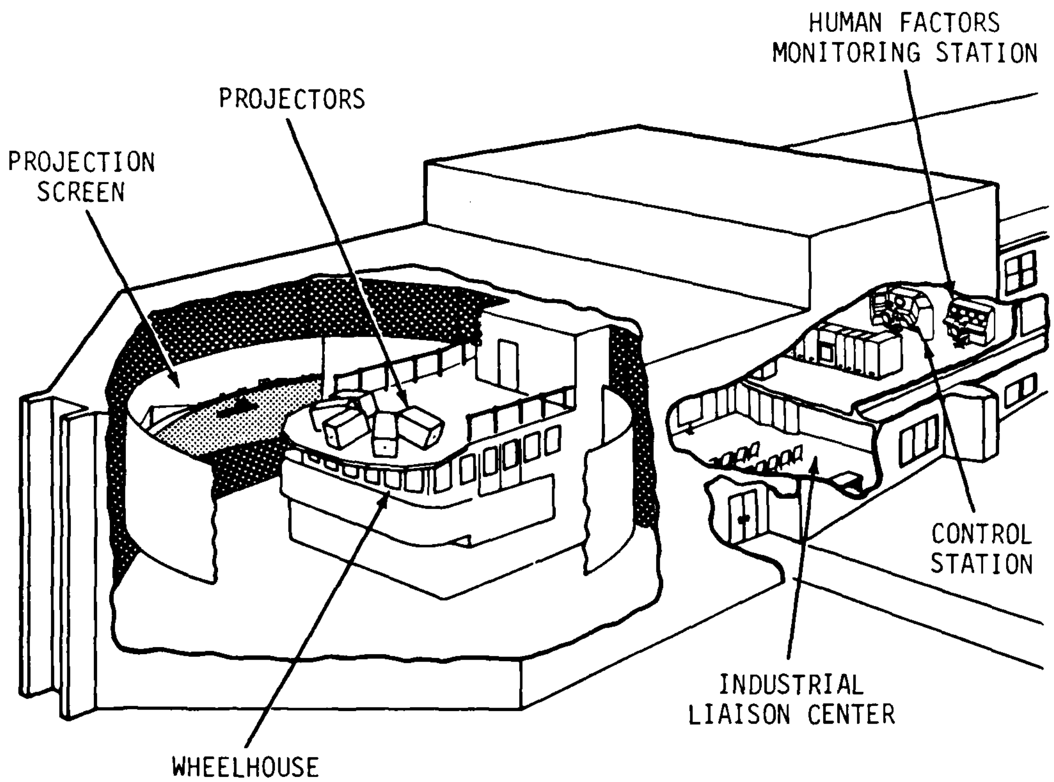

Figure A-1. Cutaway of CAORF Building

- **Steering Controls And Displays** - a gyropilot helm unit with standard steering modes, rate of turn indicator, rudder angle/rudder order indicators, and gyro repeaters.

- **Propulsion Controls and Displays** - an engine control panel (capable of simulating control from either bridge or engine room) containing a combined engine order telegraph/throttle, an rpm indicator and a switch for selecting the operating mode, such as finished with engine, warm up, maneuvering and sea speed.

- **Thruster Controls and Displays** - bow and stern thrusters and their respective indicators and status lights.

- **Navigation Systems** - two radars capable of both relative and true motion presentations, plus a collision avoidance system. Capability exists for future additions such as a digital fathometer, Radio Direction Finder, and Loran C and Omega systems.

- **Communications** - simulated VHF/SSB radio, docking loudspeaker (talkback) system, sound powered phones and ship's whistle.

- **Wind Indicators** - indicate to the bridge crew the true speed and direction of simulated wind.

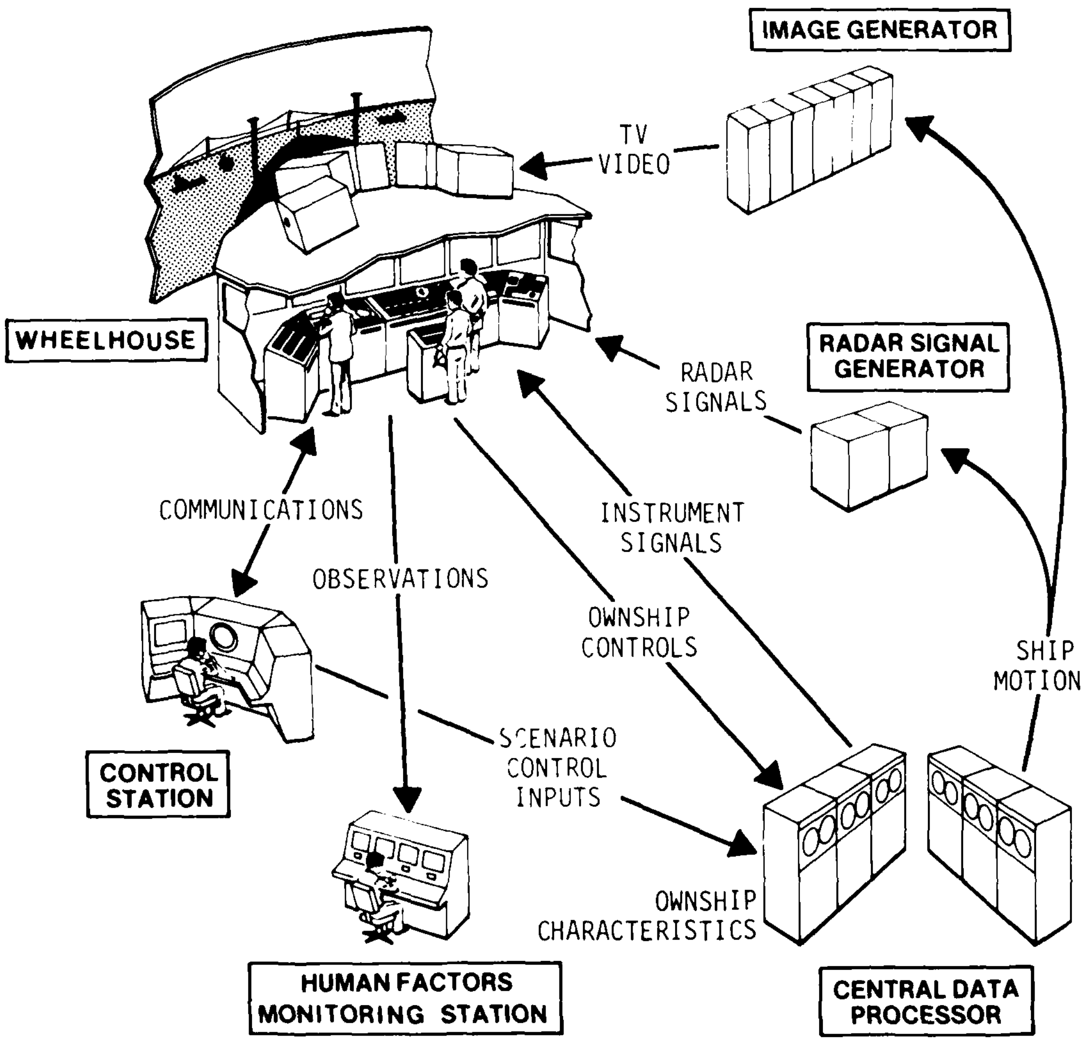

Figure A-2. Major CAORF Subsystems

A.3 OWNSHIP SIMULATION

Any ship can be simulated at CAORF. The computerized equations of motion are adapted to the ship by changing specific coefficients, among which are hydrodynamic, inertial, propulsion, thruster, rudder, aerodynamic, etc. Wind and currents realistically affect ship motion according to draft (loaded or ballasted) and relative speed and direction. Ownship's computer model was validated by comparing various simulated maneuvers (e.g., zig-zag, turning circle, spiral, crash stop, and acceleration tests) with sea trial data.

A.4 IMAGE GENERATION

The visual scene is generated at CAORF to a degree of realism sufficient for valid simulation. The scene (Figure A-3) includes all the man-made structures and natural components of the surrounding scene that mariners familiar with the geographical area deem necessary as cues for navigation.

Thus, bridges, buoys, lighthouses, tall buildings, mountains, glaciers, piers, coastlines, and islands would be depicted in the scene. In addition, the closest traffic ships and the forebody of

Figure A-3. Typical Simulated Visual Scene at CAORF

FIGURE A-3. TYPICAL SIMULATED VISUAL SCENE AT CAORF

ownship appear. All elements in the scene appear to move in response to ownship's maneuvers. The sky is depicted without clouds and the water without waves.

For enhanced realism the scene is projected in full color. The perspective is set for the actual bridge height above waterline for the simulated ship. Shadowing can be varied according to the position of the sun at different times of day.

Environmental conditions also affect the scene. The lighting can be varied continuously from full sun to moonless night. At night, lights can be seen on traffic vessels, buoys, piers, and other points ashore. Visibility in the day or night can be reduced to simulate any degree of fog or haze.

A.5 RADAR SIGNAL GENERATION

The Radar Signal Generator produces real-time video signals for driving the two radar PPIs. The items displayed are synchronized with the visual scene and include navigation aids, ships, shorelines and other topographical features with appropriate target shadowing, clutter, range attenuation, and receiver noise. The radar gaming area, which covers an area of 150 by 200 miles, extends beyond the visual gaming area, which is 50 by 100 miles. Within the radar gaming area, as many as 40 moving traffic ships can be displayed. The radar signal generator also drives the collision avoidance system, which can be slaved to either of the master PPIs.

A.6 CONTROL STATION

The Control Station (Figure A-4) is the central location from which the simulator experiment is controlled and monitored. An experiment can be initiated anywhere within the visual gaming area with any ship traffic configuration. The Control Station enables the researchers to interface with the watchstanding crew on the bridge, to simulate malfunctions, and to control the operating mode of the simulator. The Control Station is also capable of controlling motions of traffic ships and tugs in the gaming area and simulating telephone, intercom, radio (VHF, SSB) and whistle contact with the CAORF bridge crew.

A.7 HUMAN FACTORS MONITORING STATION

The Human Factors Monitoring Station (Figure A-5) is designed to allow collection of data on crew behavior. Monitoring data is provided by five closed-circuit TV cameras and four microphones strategically located throughout the wheelhouse to record all activities, comments and commands.

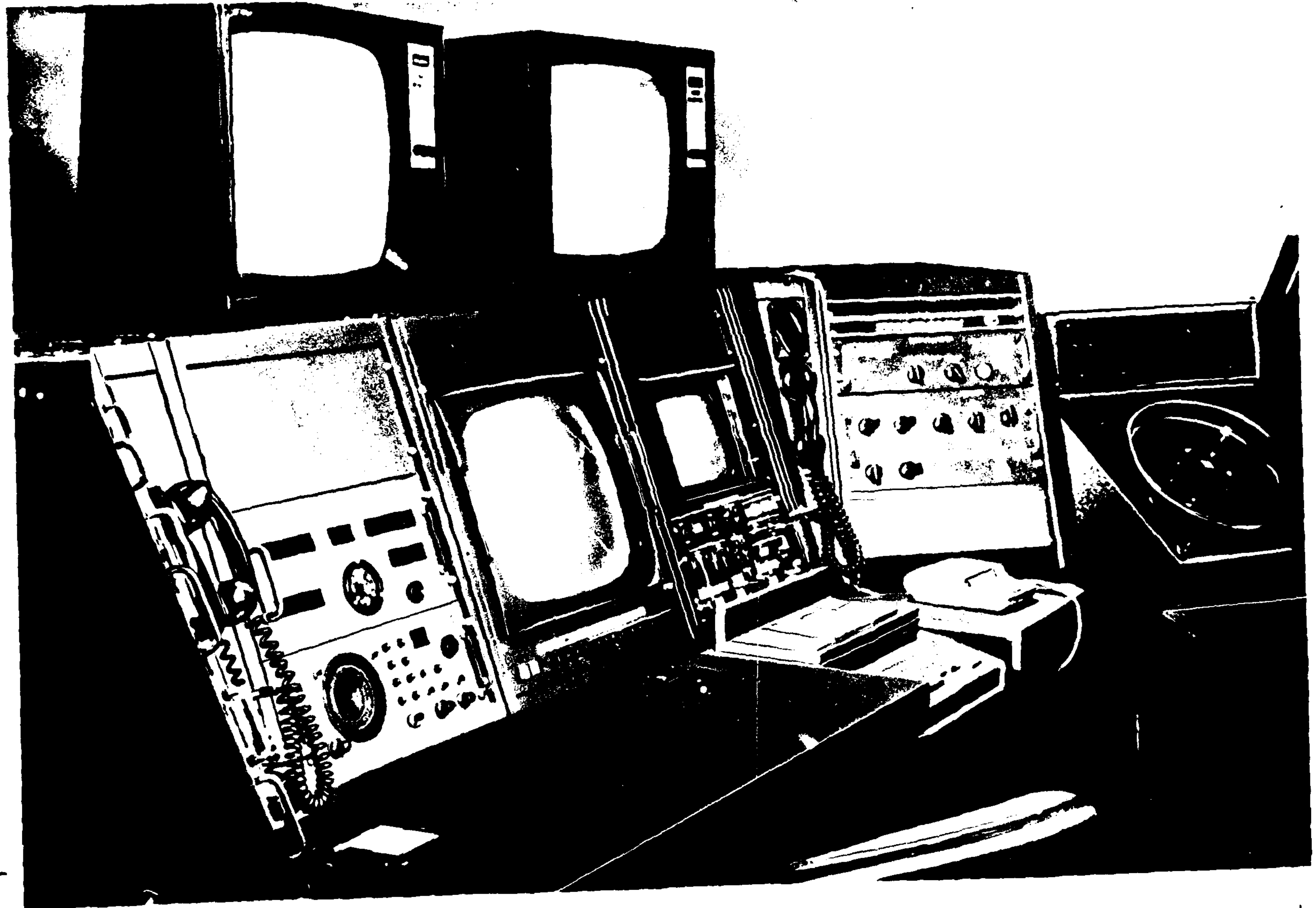

FIGURE A-4. CONTROL STATION

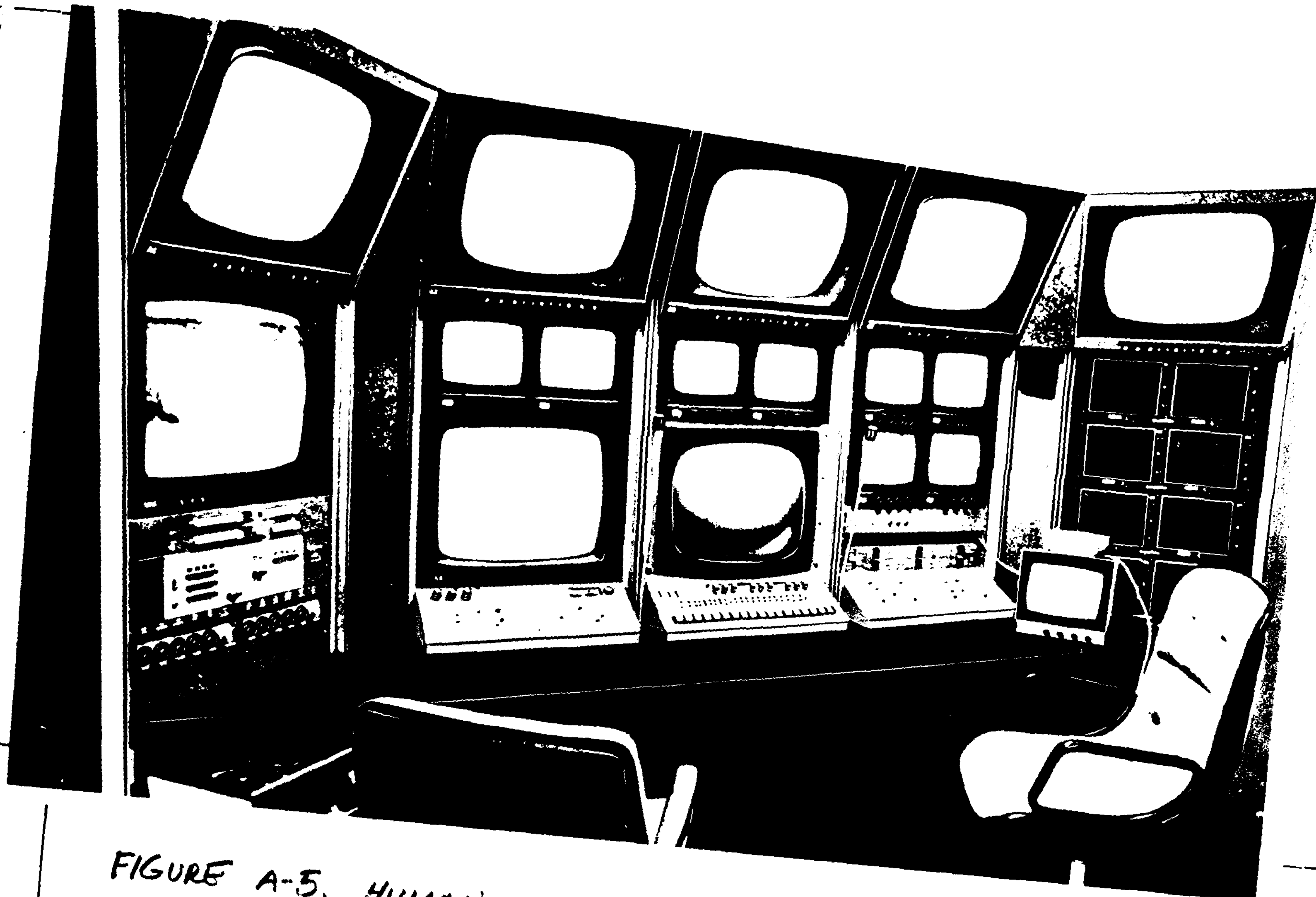

FIGURE A-5. HUMAN FACTORS MONITORING STATIO[illegible]

APPENDIX B

WATCH ORDERS

INSTRUCTIONS TO PILOTS: OUTBOUND

You are in command of an 80,000 DWT tanker bound for sea. Severe accumulations of ice have built up at the Hook. In addition, many buoys are missing and several are off station. (Refer to attached chart, Figure B-1.) You are asked to navigate the vessel in the best manner possible using the aids available. A qualified mate and helmsman are available to support you as directed.

Vessel Particulars (80,000 DWT)

Length	233 meters (763 feet)
Beam	38 meters (125 feet)
Draft	9 meters (30 feet)

Water Depth

10.67 meters (35 feet)

Current/Wind

2 hours before high water (1.5 knots, flood). No wind.

Radar

Not operative

Initial Conditions

Heading 106° T
Last order midship
Speed - 74 RPM; 13 knots
Pelorus available

INSTRUCTIONS TO PILOTS: INBOUND

You are in command of an 80,000 DWT tanker bound for Raritan Bay under ice conditions. Severe accumulations of ice have built up at the Hook. In addition, many buoys are missing and several are off station. (Refer to attached chart, Figure B-2.) You are asked to navigate the vessel in the best manner possible using the aids available. A qualified mate and helmsman are available to support you as directed.

Vessel Particulars (80,000 DWT)

Length	233 meters (763 feet)
Beam	38 meters (125 feet)
Draft	9 meters (30 feet)

Water Depth

10.67 meters (35 feet)

Current/Wind

2 hours before high water (1.5 knots, flood). No wind.

Radar

Not operative

Initial Conditions

Heading 308° T
Last order midship
Speed - 74 RPM; 13 knots
Pelorus available

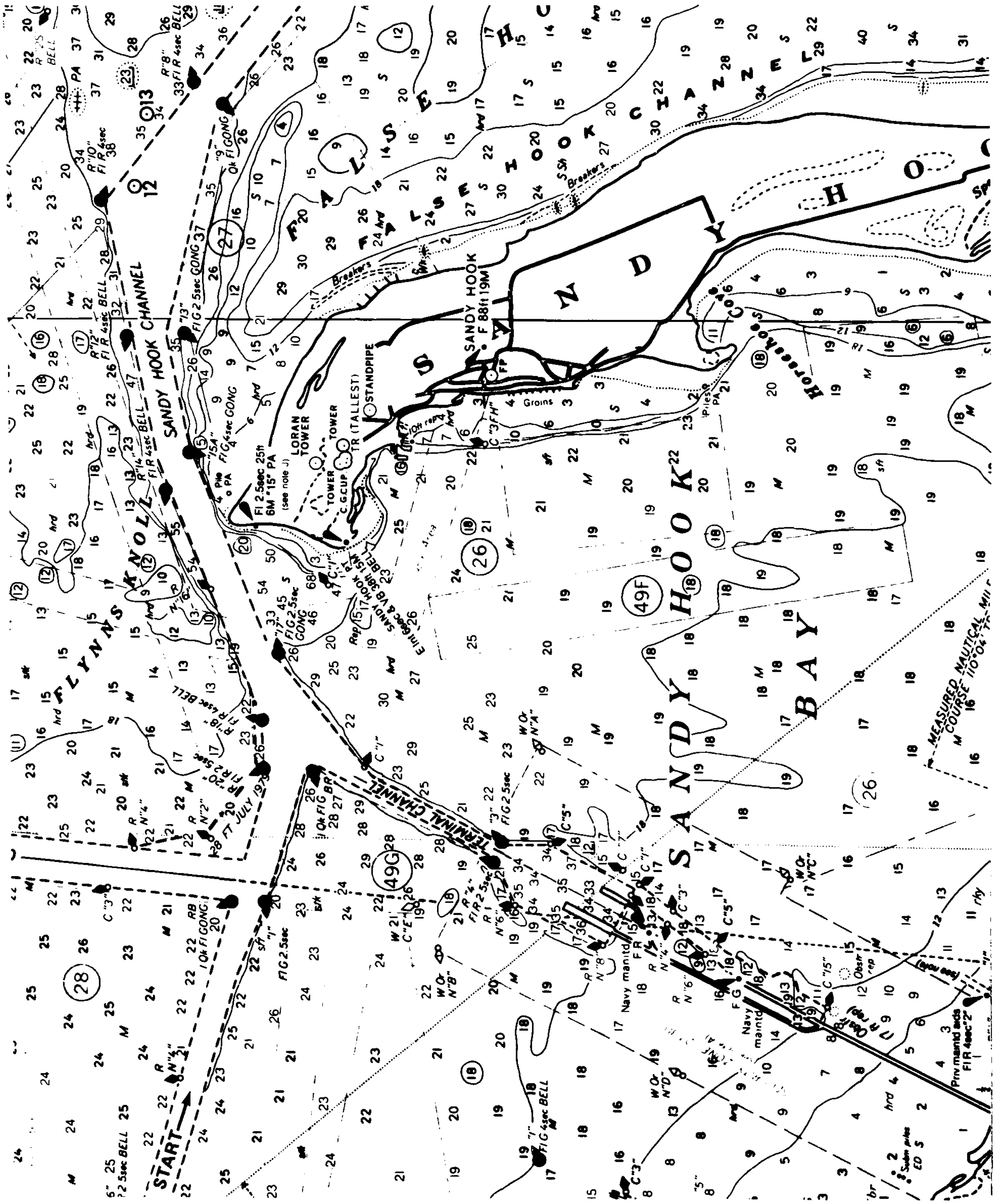

Figure B-1. Chart Used by Test Subjects for Outbound Runs

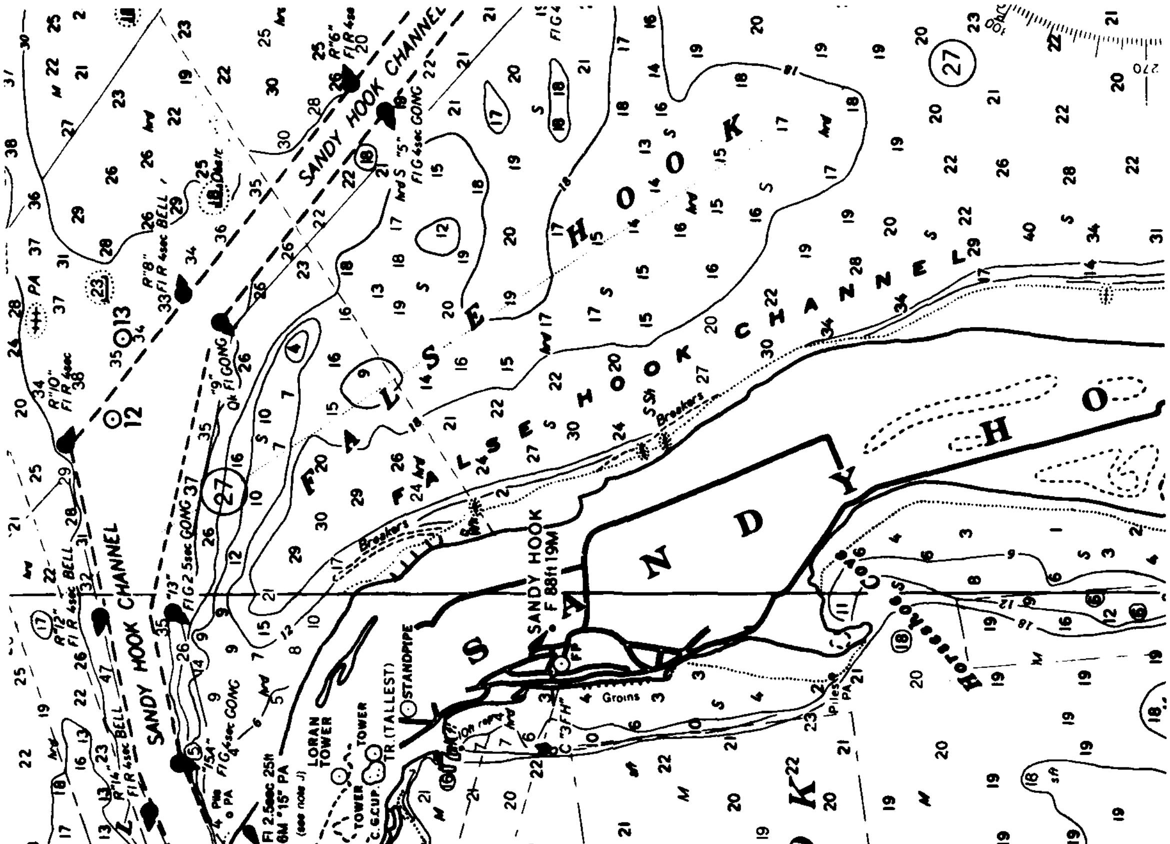

Figure B-2. Chart Used by Test Subjects for Inbound Runs

APPENDIX C

DATA PLOTS OF VESSEL TRACKS, VISUAL-ONLY MODE

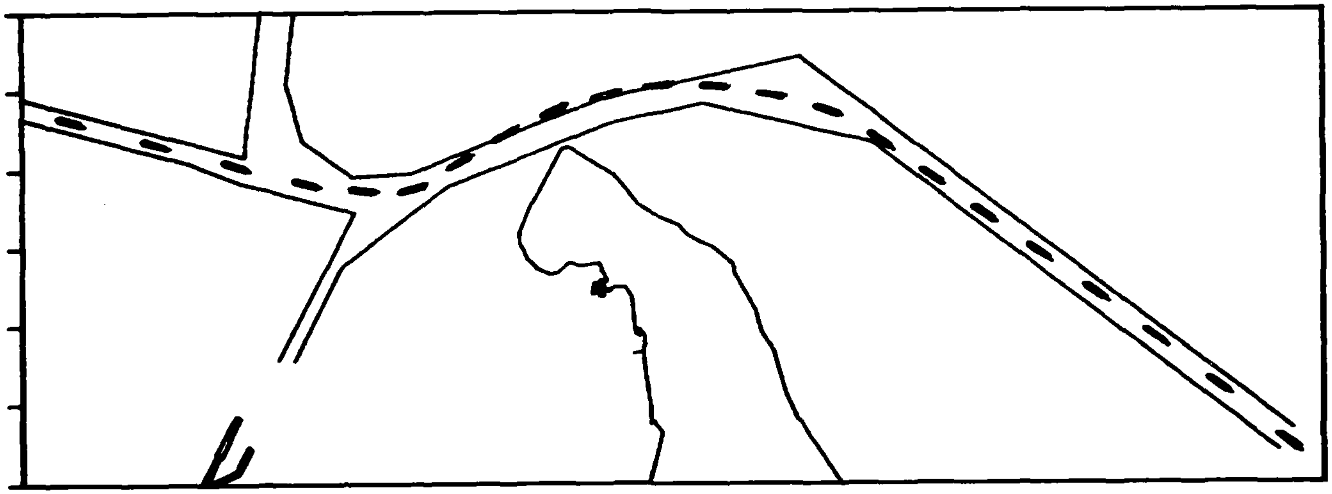

Figure C-1. Inbound Run, Visual-Only Mode, Test Subject 1

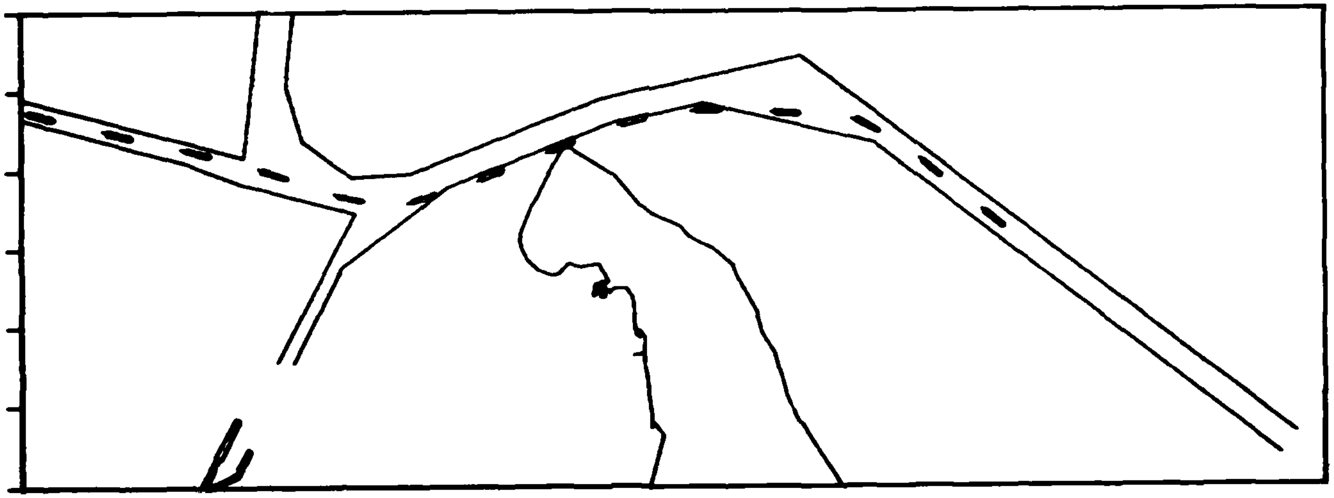

Figure C-2. Outbound Run, Visual-Only Mode, Test Subject 1

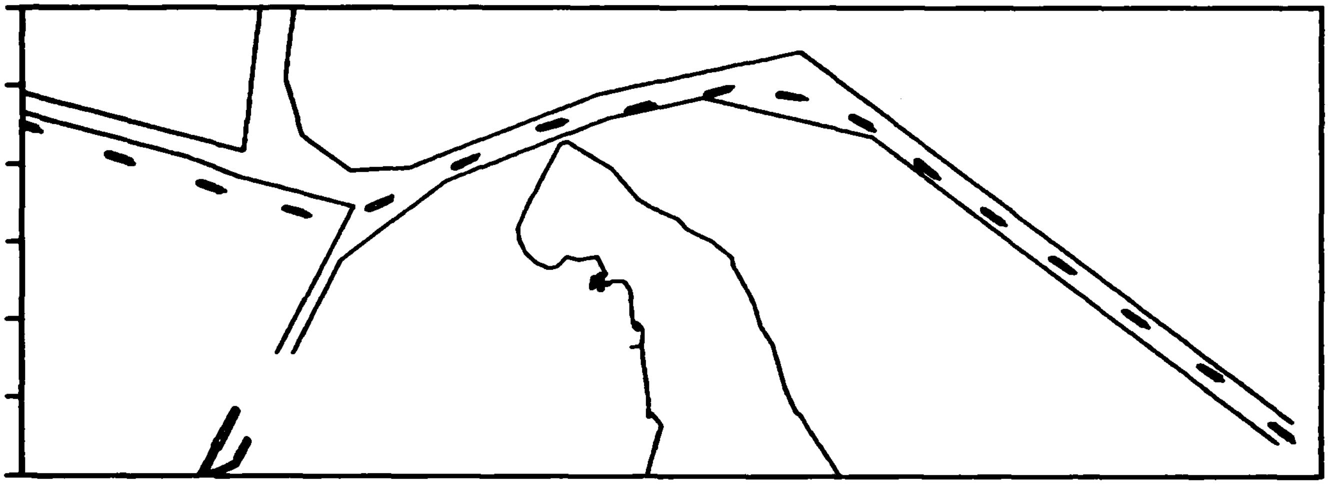

Figure C-3. Inbound Run, Visual-Only Mode, Test Subject 2

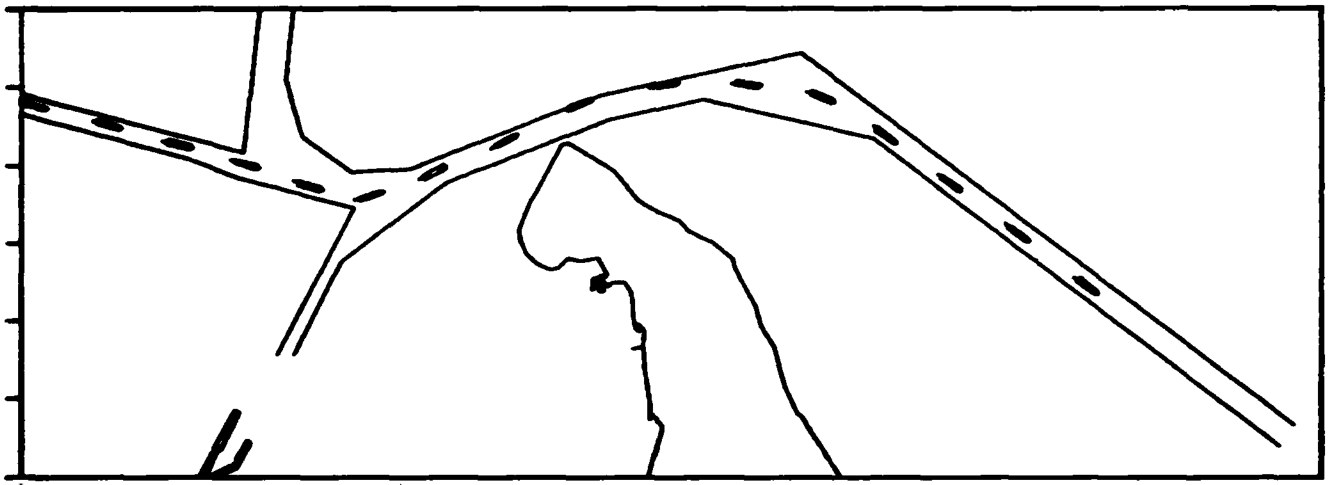

Figure C-4. Outbound Run, Visual-Only Mode, Test Subject 2

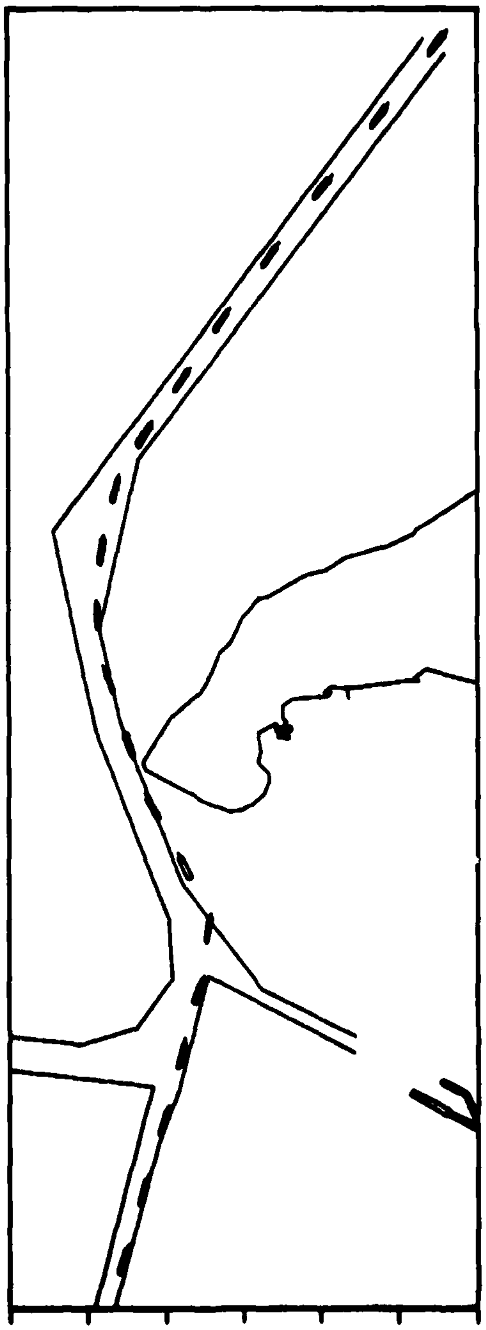

Figure C-5. Inbound Run, Visual-Only Mode, Test Subject 3

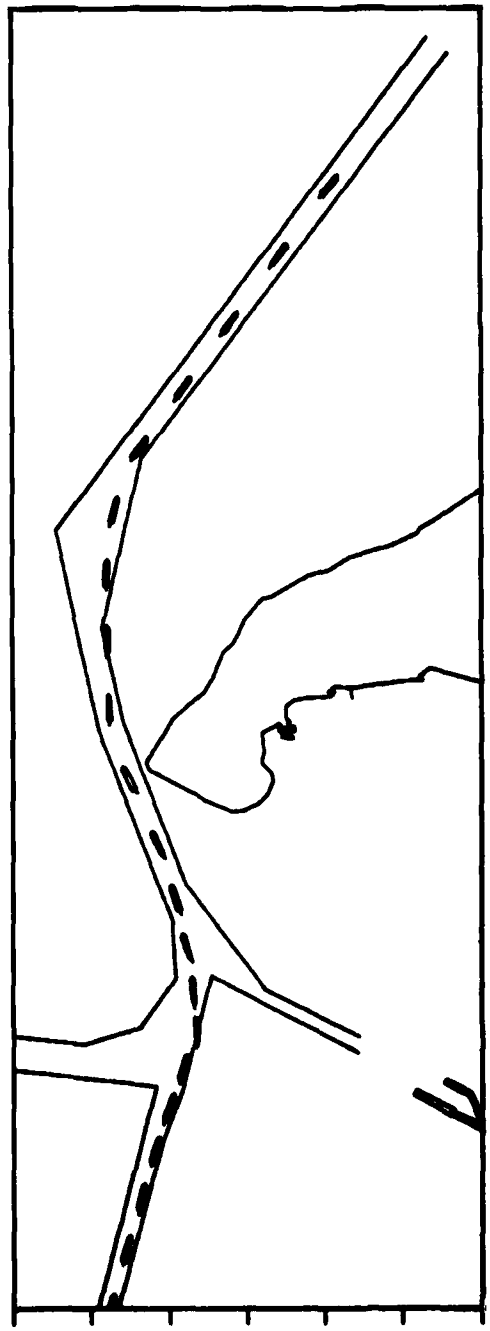

Figure C-6. Outbound Run, Visual-Only Mode, Test Subject 3

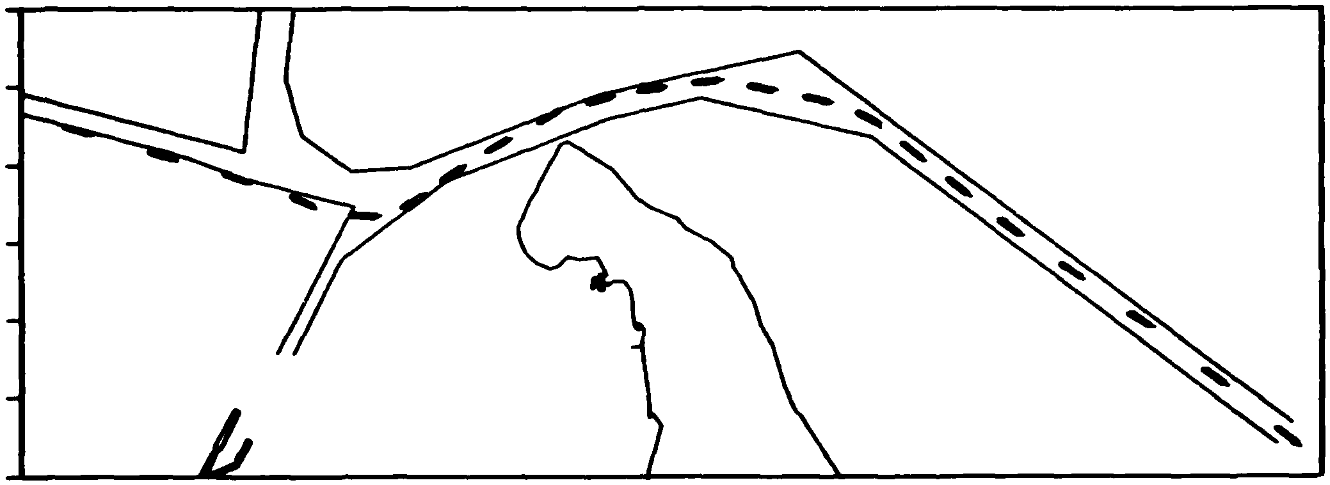

Figure C-7. Inbound Run, Visual-Only Mode, Test Subject 4

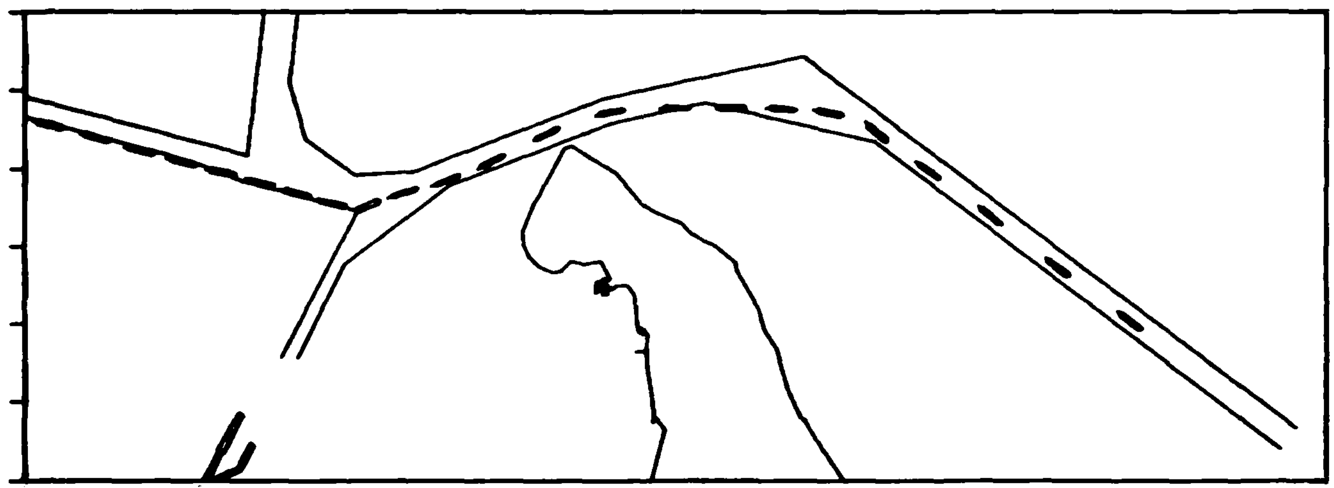

Figure C-8. Outbound Run, Visual-Only Mode, Test Subject 4

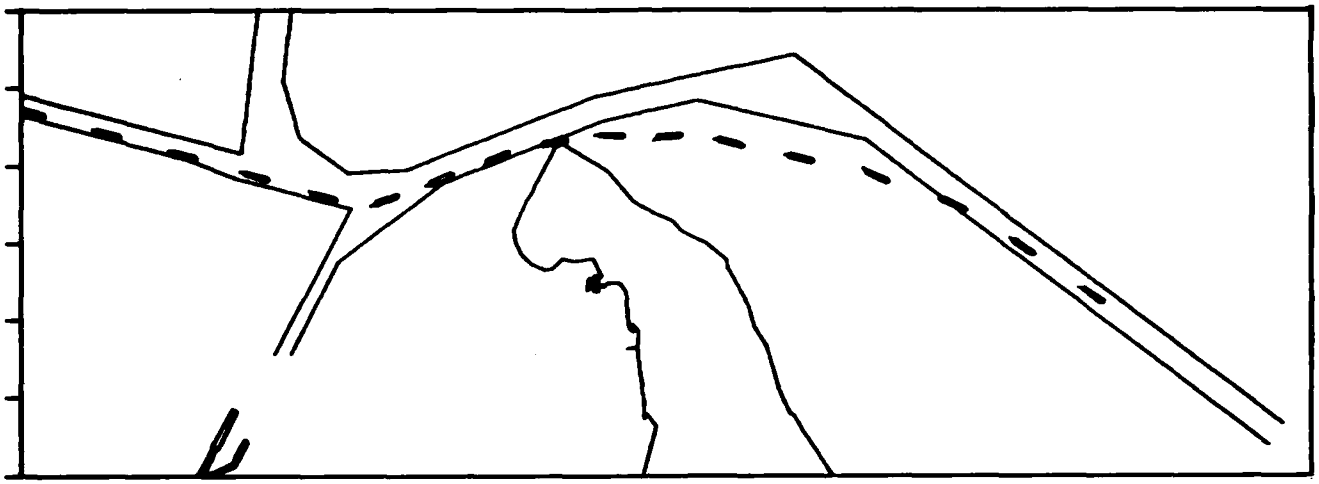

Figure C-9. Outbound Run, Visual-Only Mode, Test Subject 5

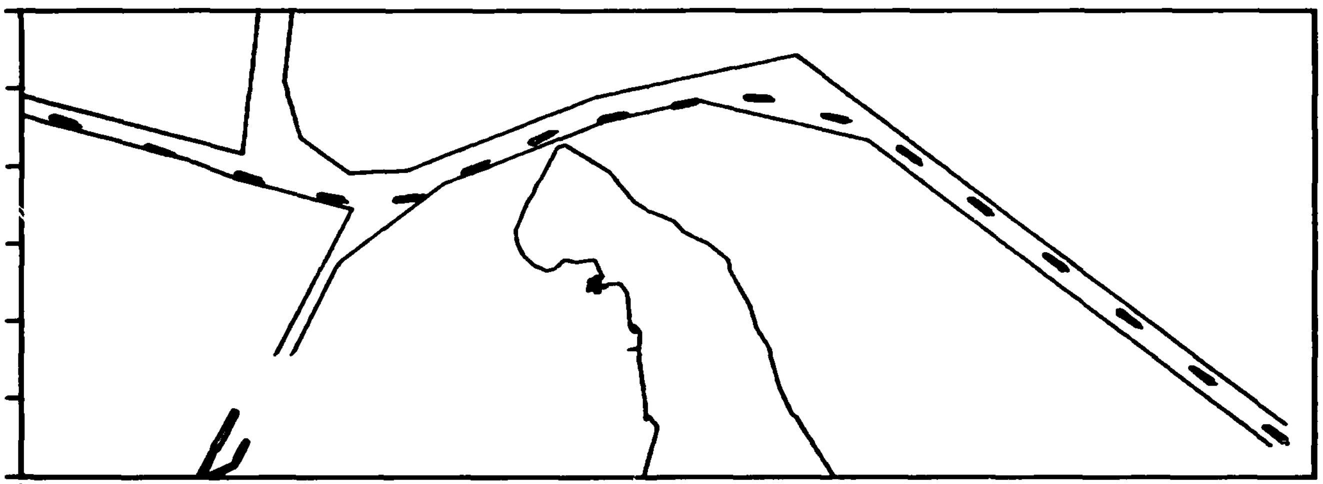

Figure C-10. Inbound Run, Visual-Only Mode, Test Subject 5

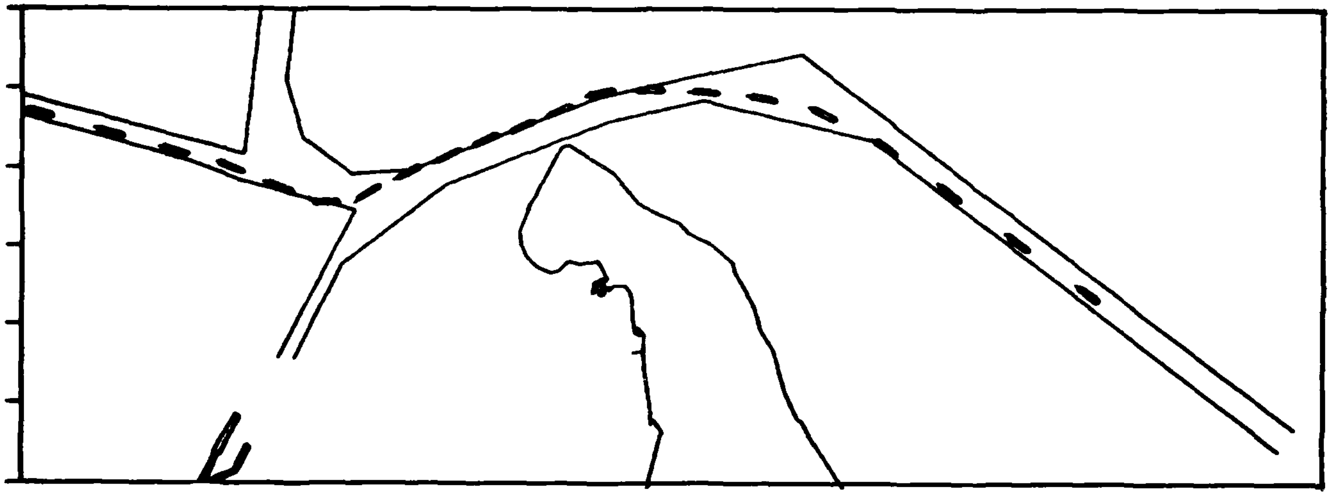

Figure C-11. Outbound Run, Visual-Only Mode, Test Subject 6

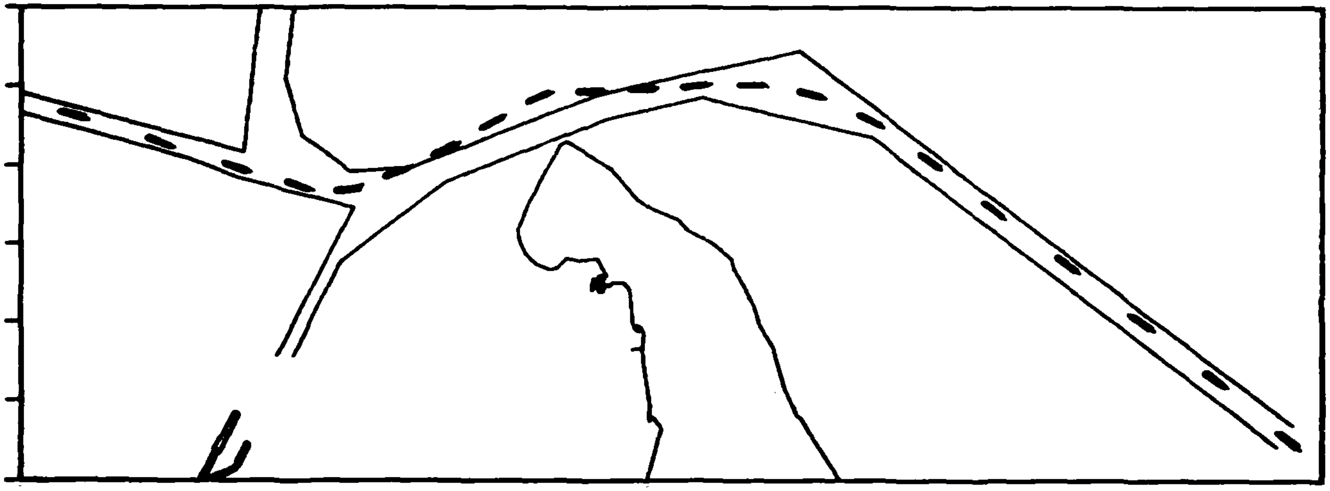

Figure C-12. Inbound Run, Visual-Only Mode, Test Subject 6

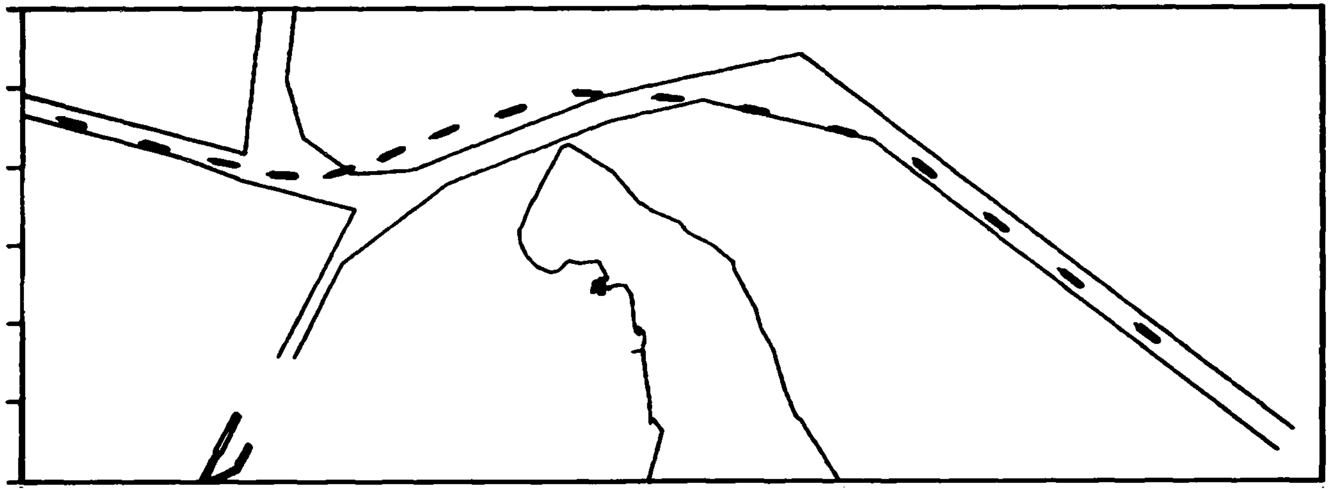

Figure C-13. Outbound Run, Visual-Only Mode, Test Subject 7

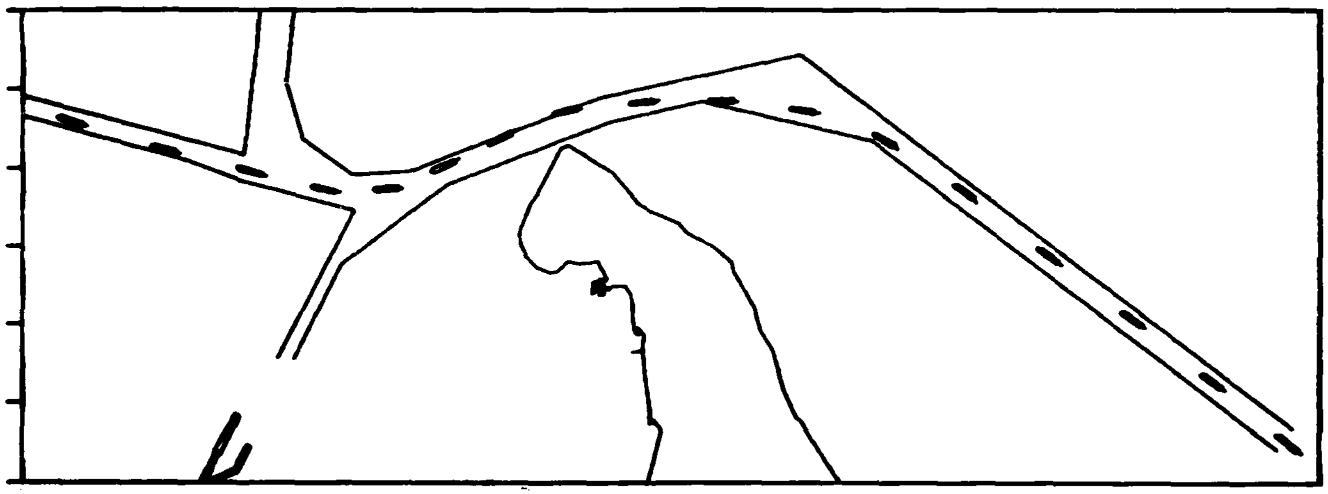

Figure C-14. Inbound Run, Visual-Only Mode, Test Subject 7

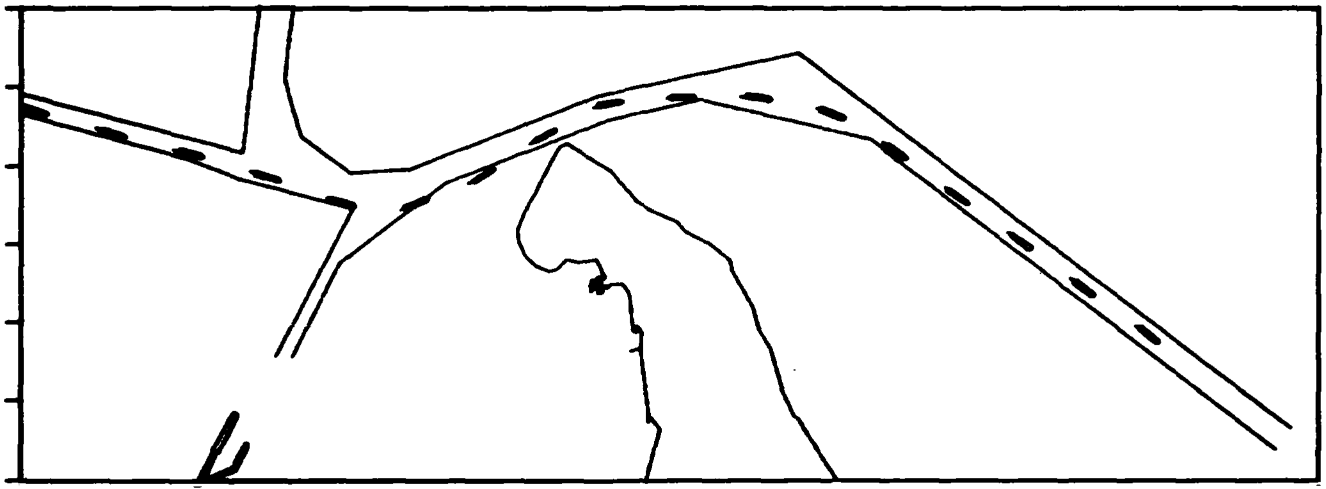

Figure C-15. Outbound Run, Visual-Only Mode, Test Subject 8

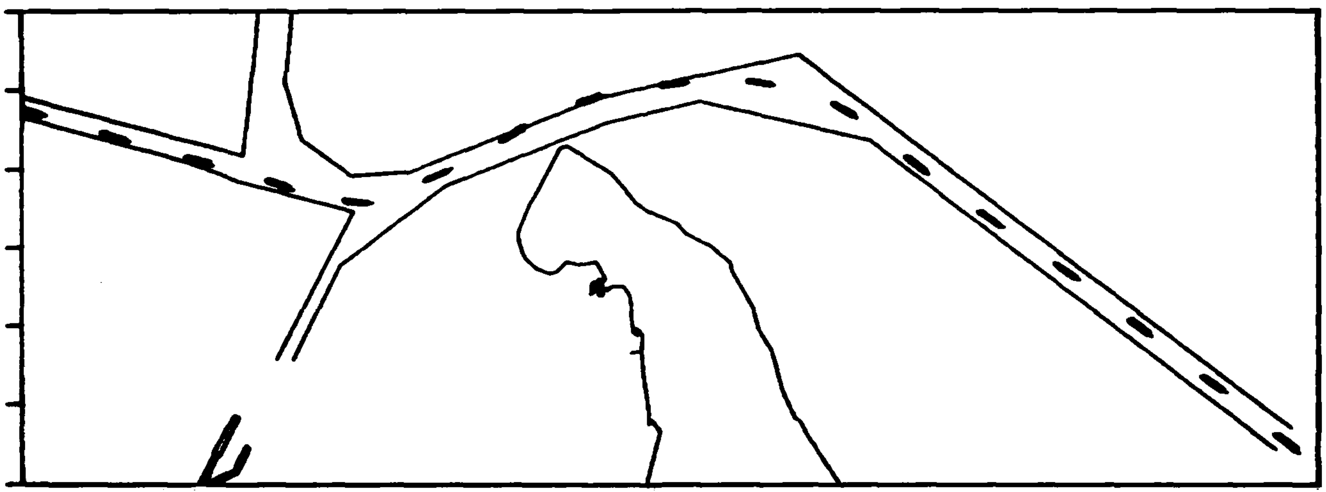

Figure C-16. Inbound Run, Visual-Only Mode, Test Subject 8

APPENDIX D

DATA PLOTS OF VESSEL TRACKS, PRECISION NAVIGATOR MODE

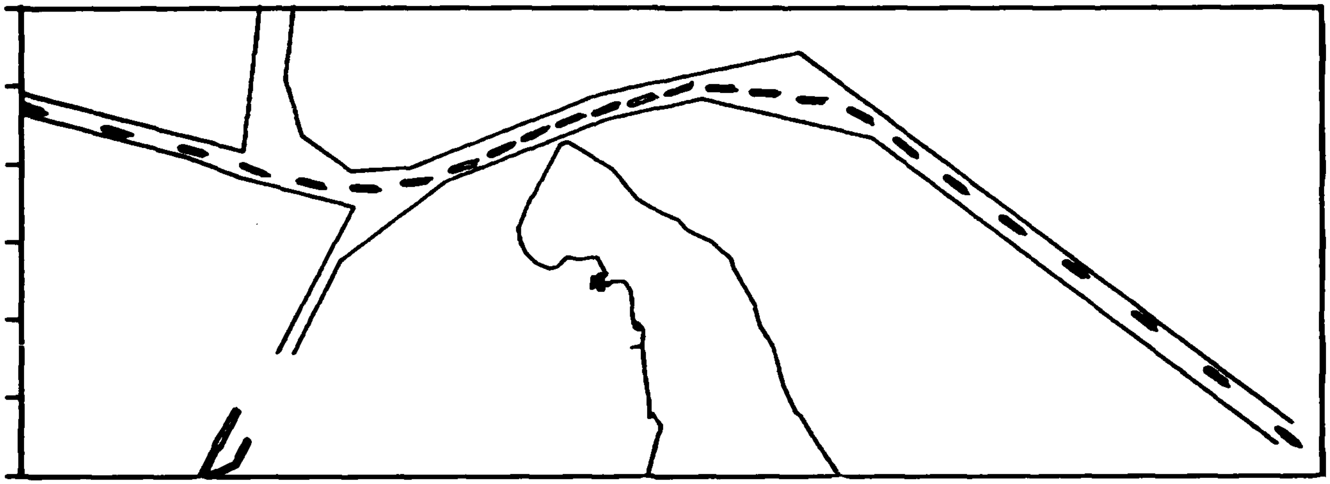

Figure D-1. Inbound Run, Precision Navigator Mode, Test Subject 9

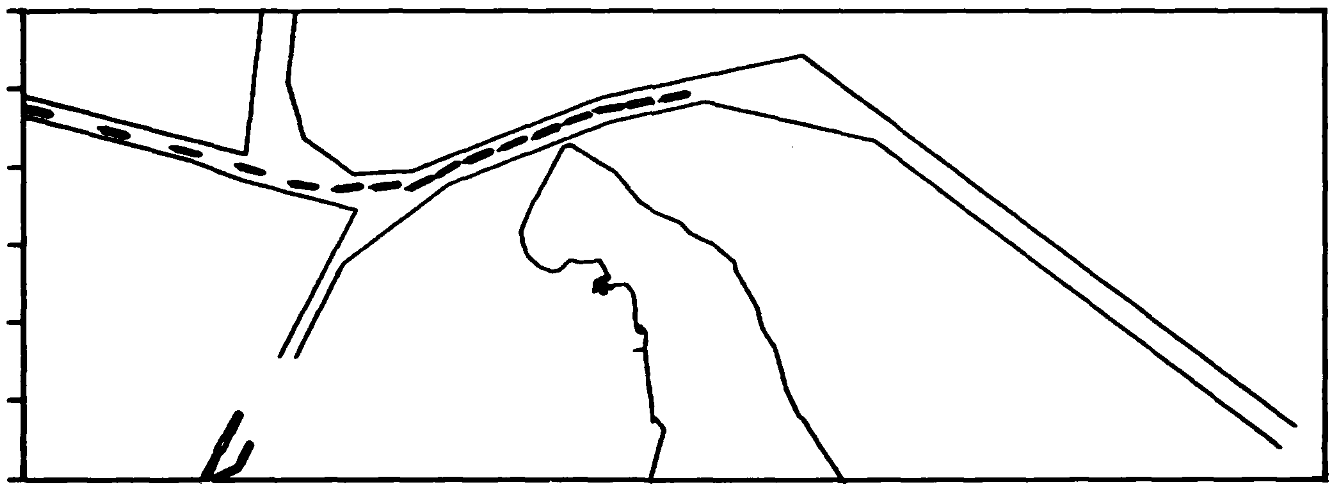

Figure D-2. Outbound Run, Precision Navigator Mode, Test Subject 9

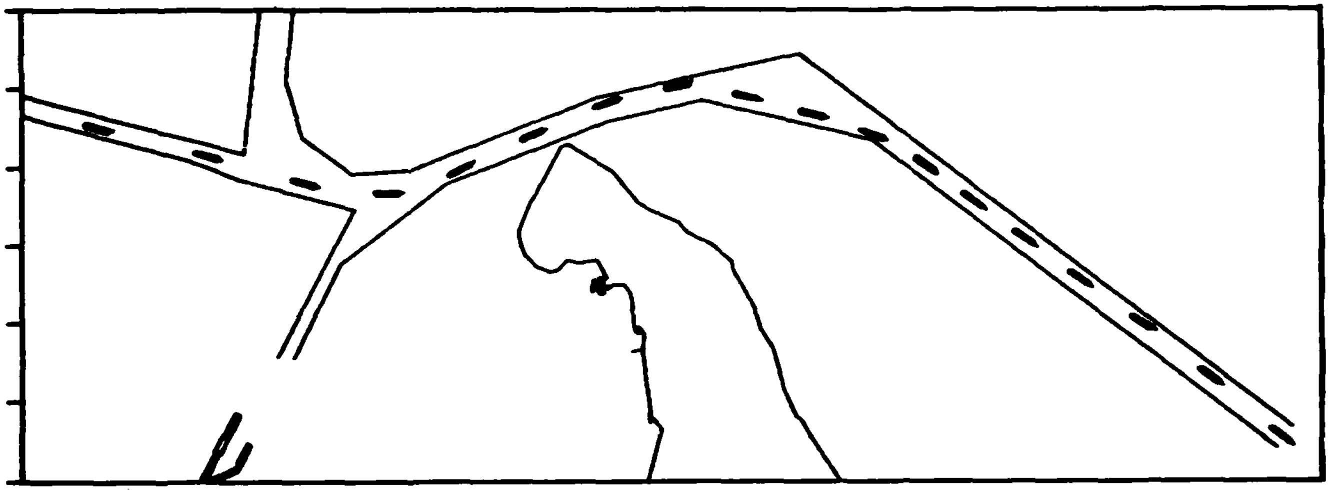

Figure D-3. Inbound Run, Precision Navigator Mode, Test Subject 10

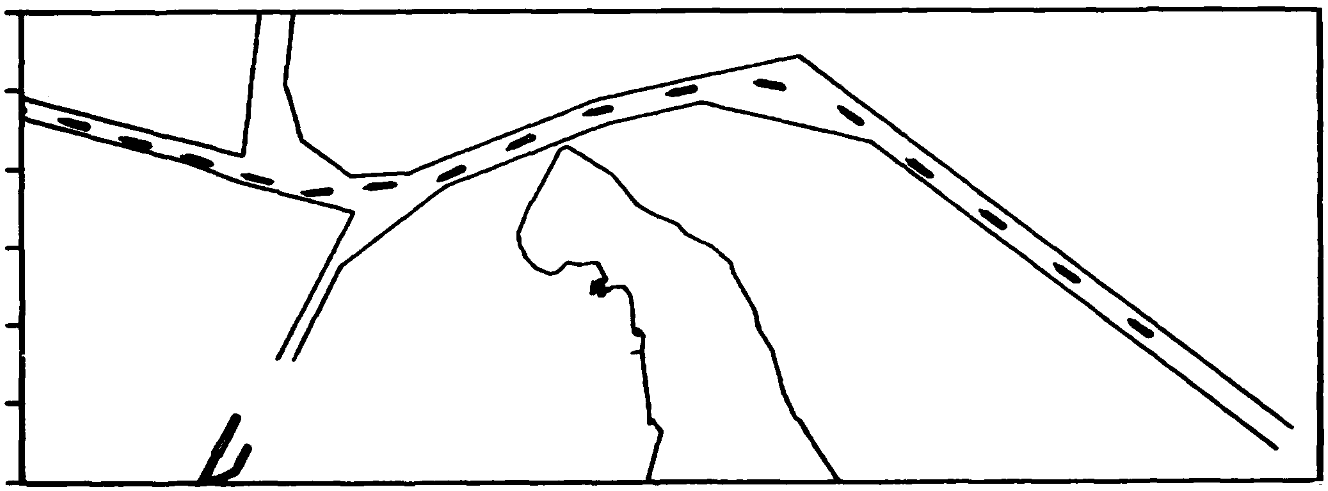

Figure D-4. Outbound Run, Precision Navigator Mode, Test Subject 10

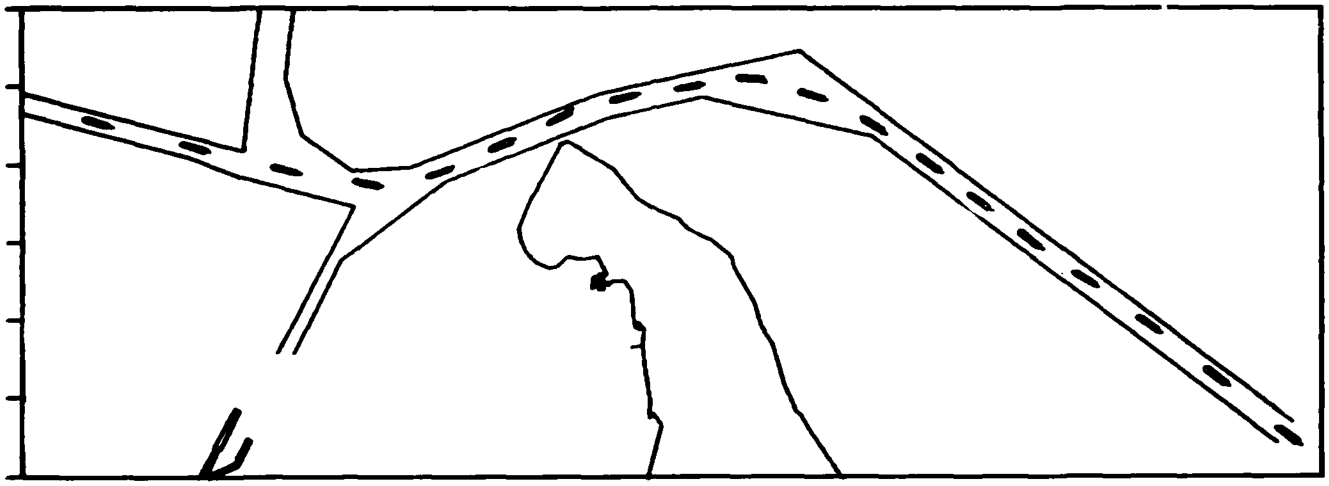

Figure D-5. Inbound Run, Precision Navigator Mode, Test Subject 11

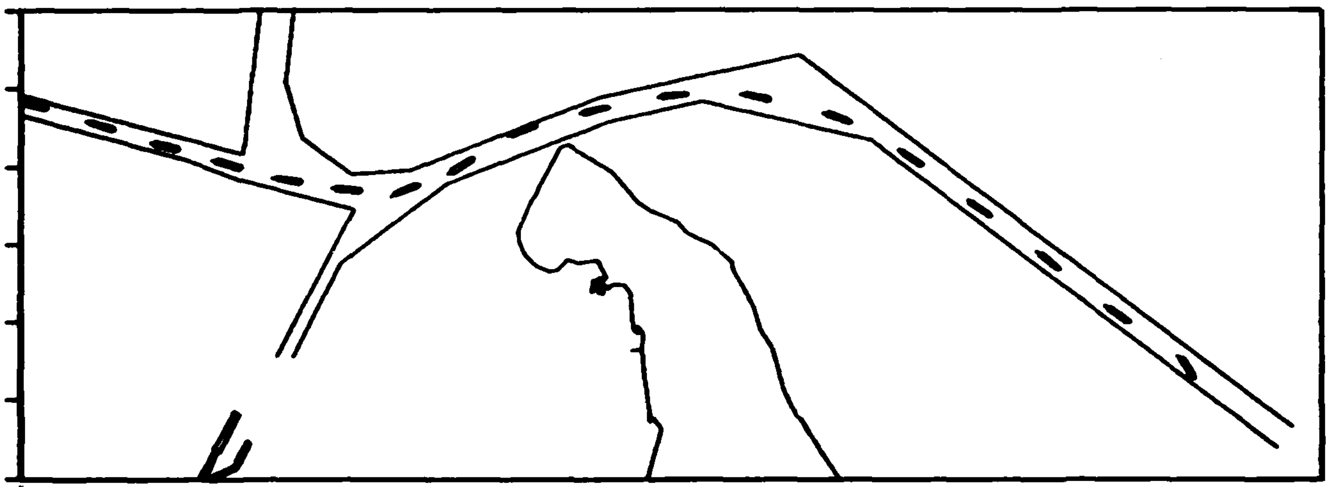

Figure D-6. Outbound Run, Precision Navigator Mode, Test Subject 11

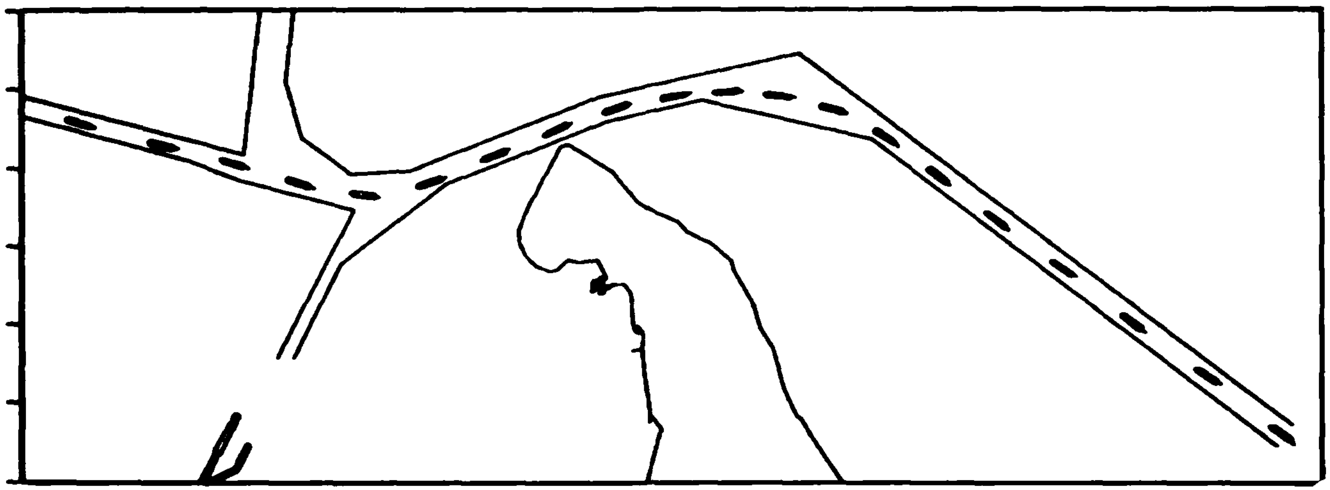

Figure D-7. Inbound Run, Precision Navigator Mode, Test Subject 12

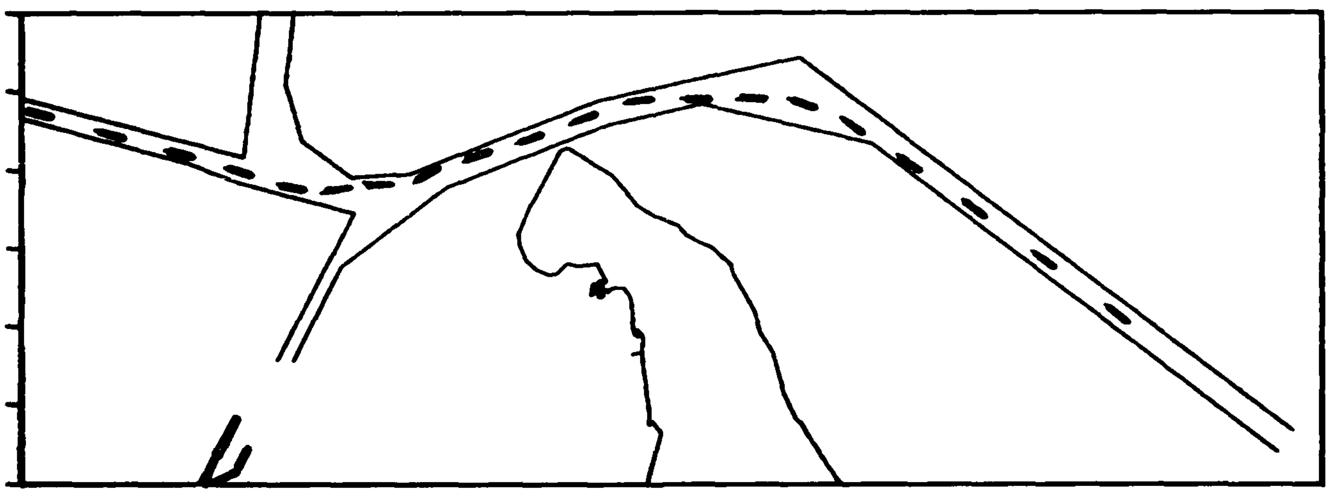

Figure D-8. Outbound Run, Precision Navigator Mode, Test Subject 12

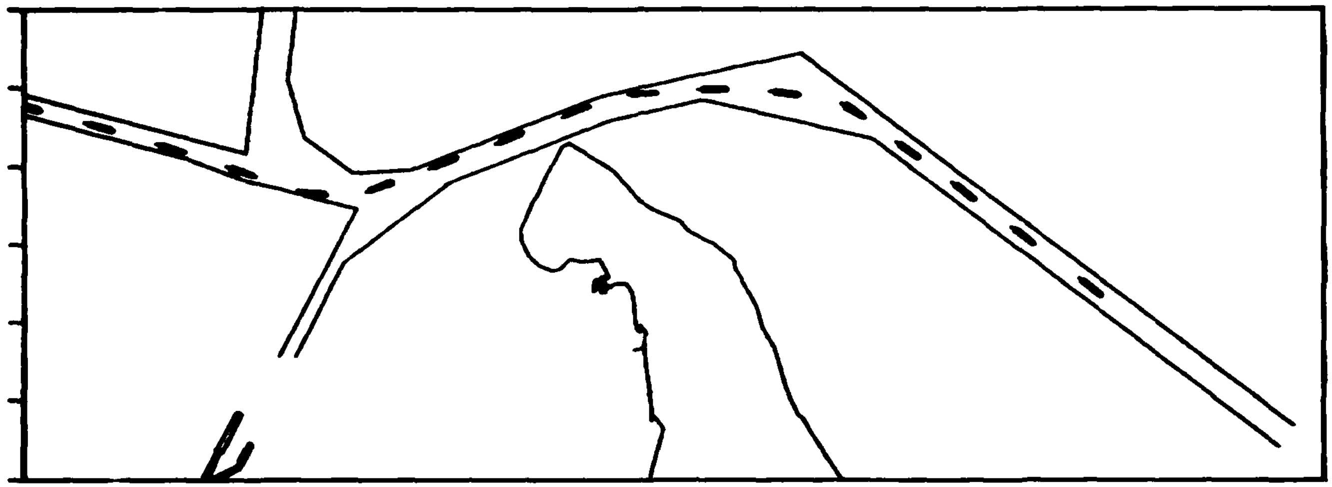

Figure D-9. Outbound Run, Precision Navigator Mode, Test Subject 13

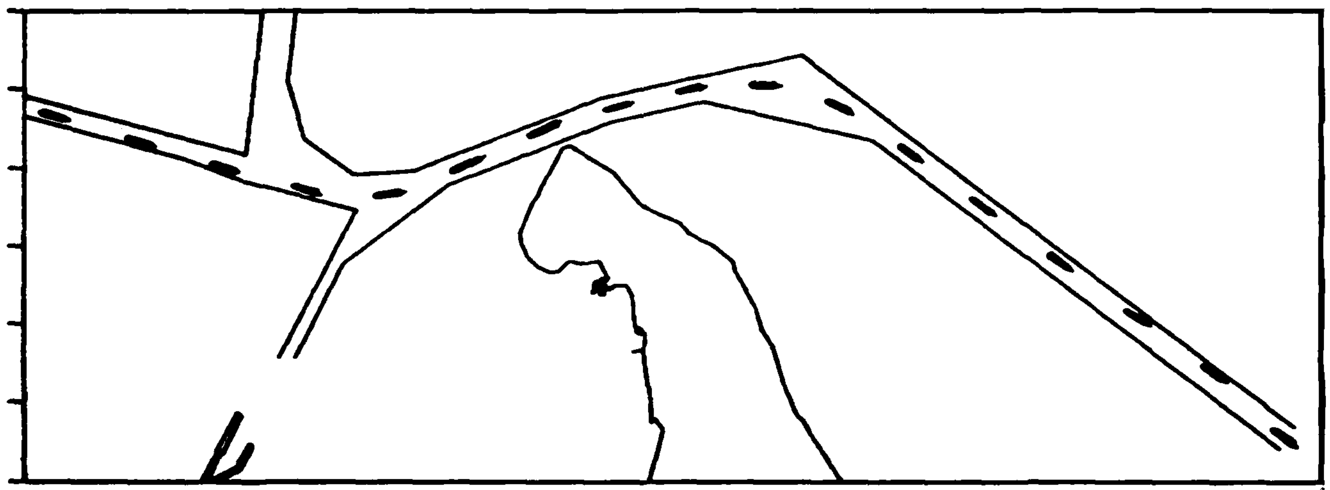

Figure D-10. Inbound Run, Precision Navigator Mode, Test Subject 13

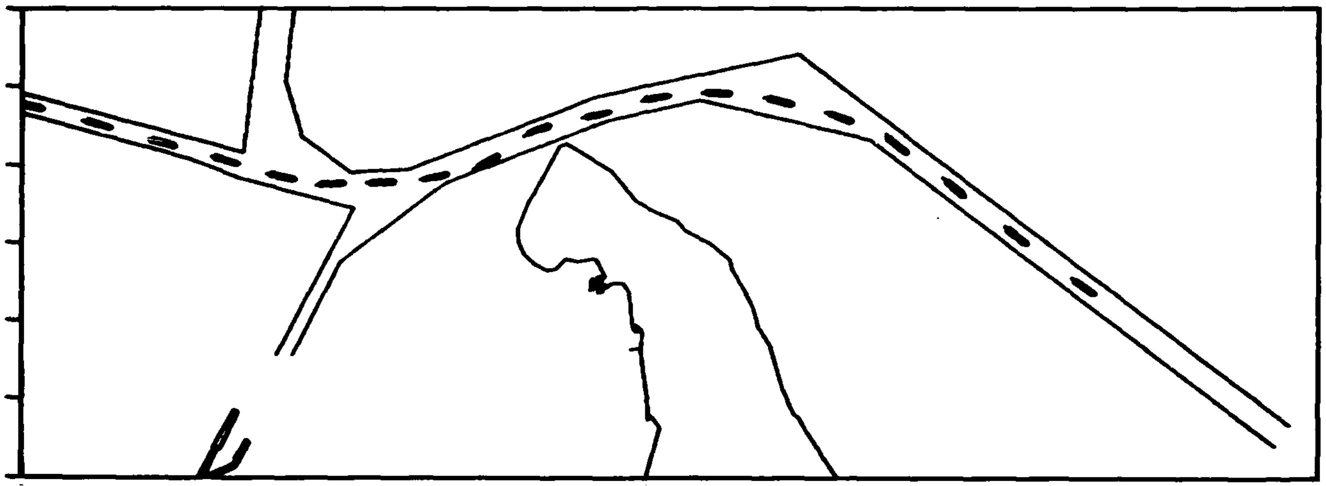

Figure D-11. Outbound Run, Precision Navigator Mode, Test Subject 14

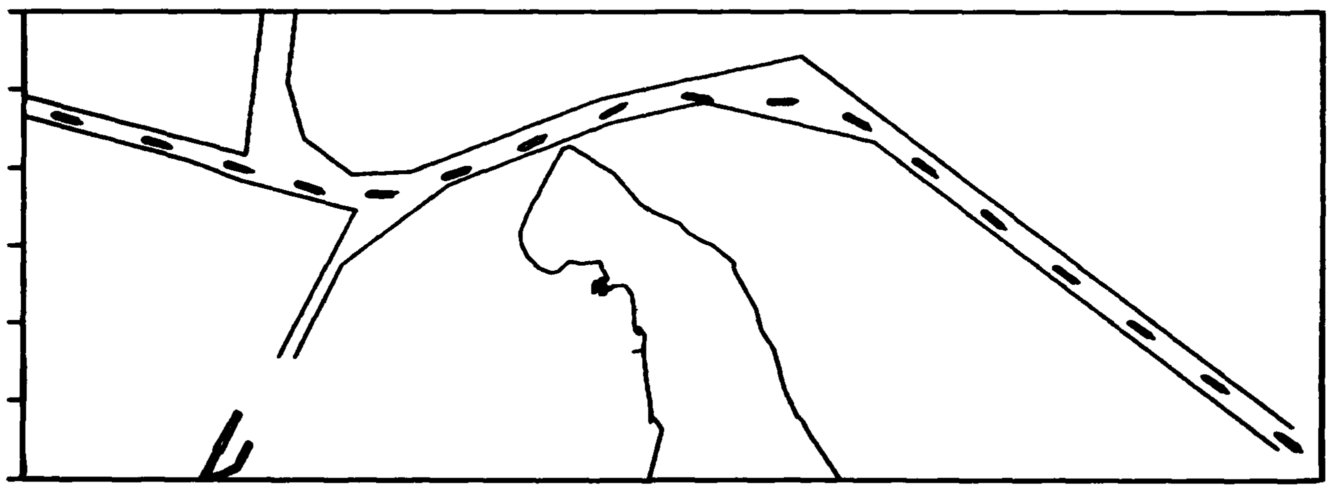

Figure D-12. Inbound Run, Precision Navigator Mode, Test Subject 14

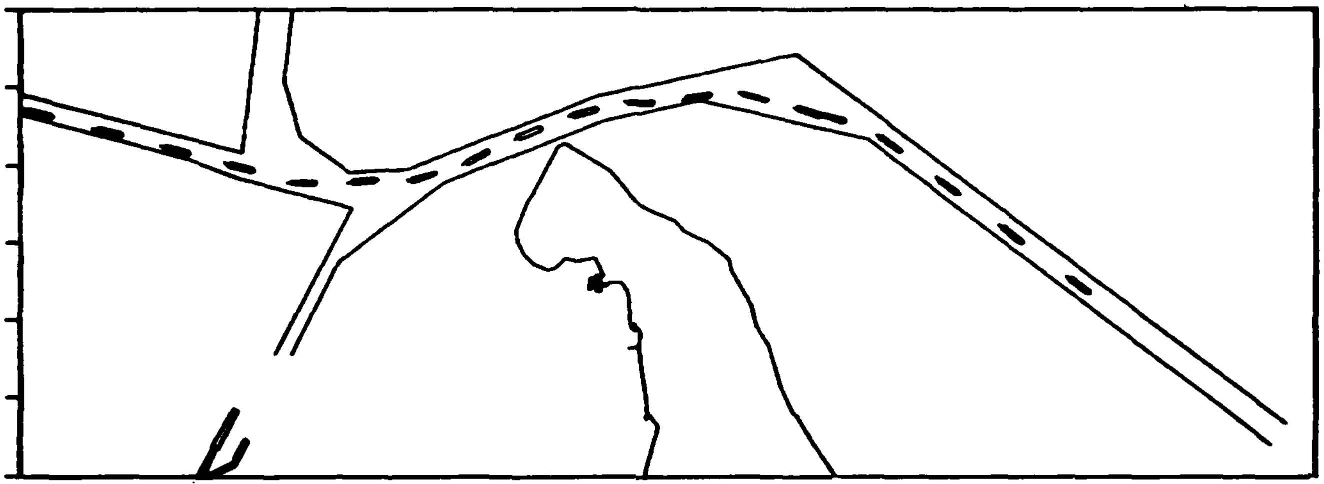

Figure D-13. Outbound Run, Precision Navigator Mode, Test Subject 15

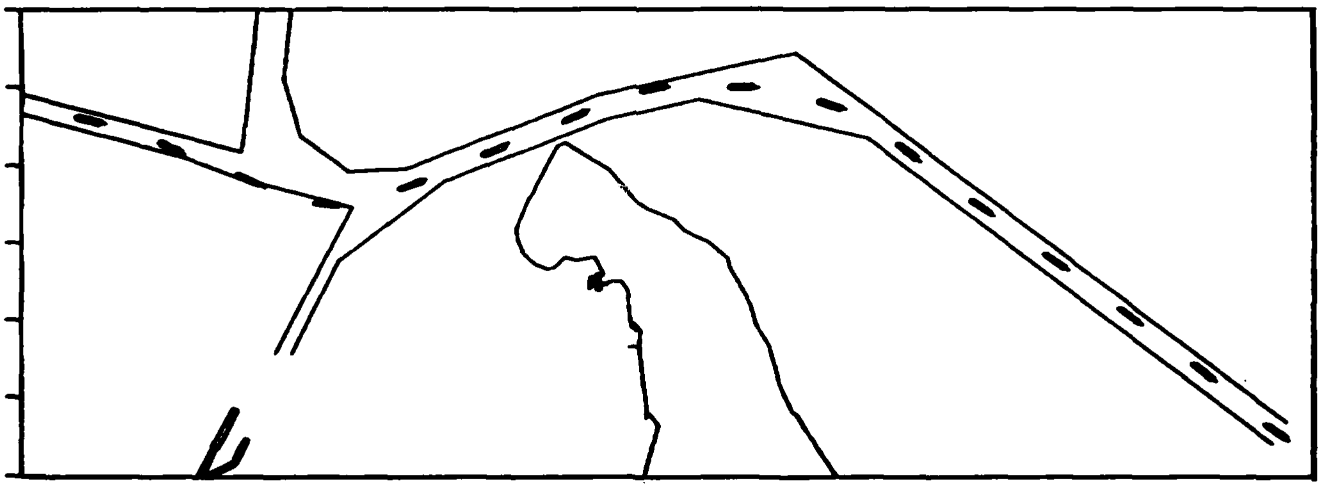

Figure D-14. Inbound Run, Precision Navigator Mode, Test Subject 15

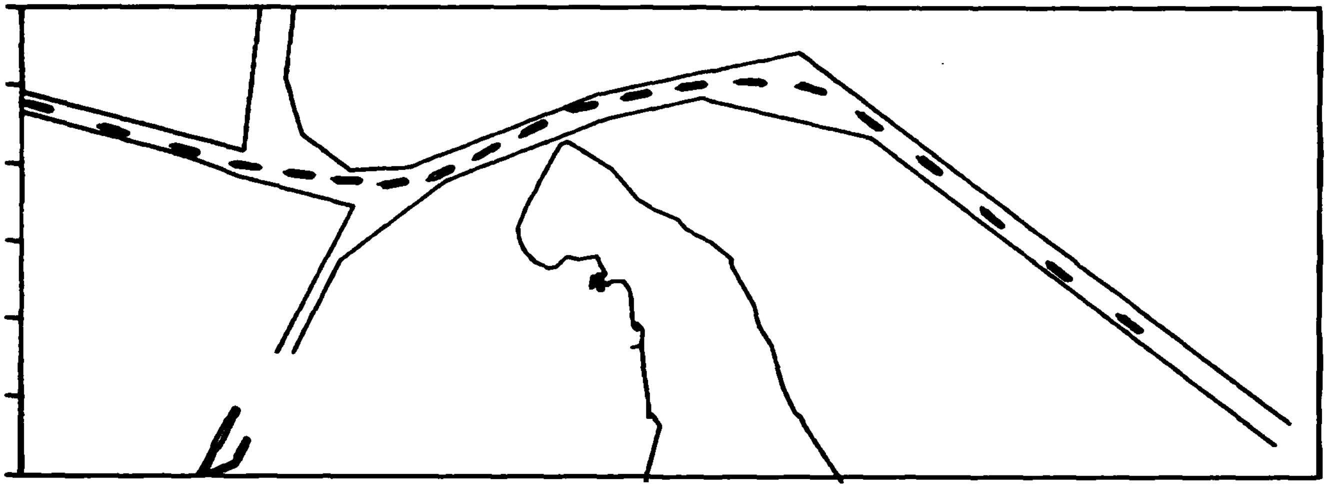

Figure D-15. Outbound Run, Precision Navigator Mode, Test Subject 16

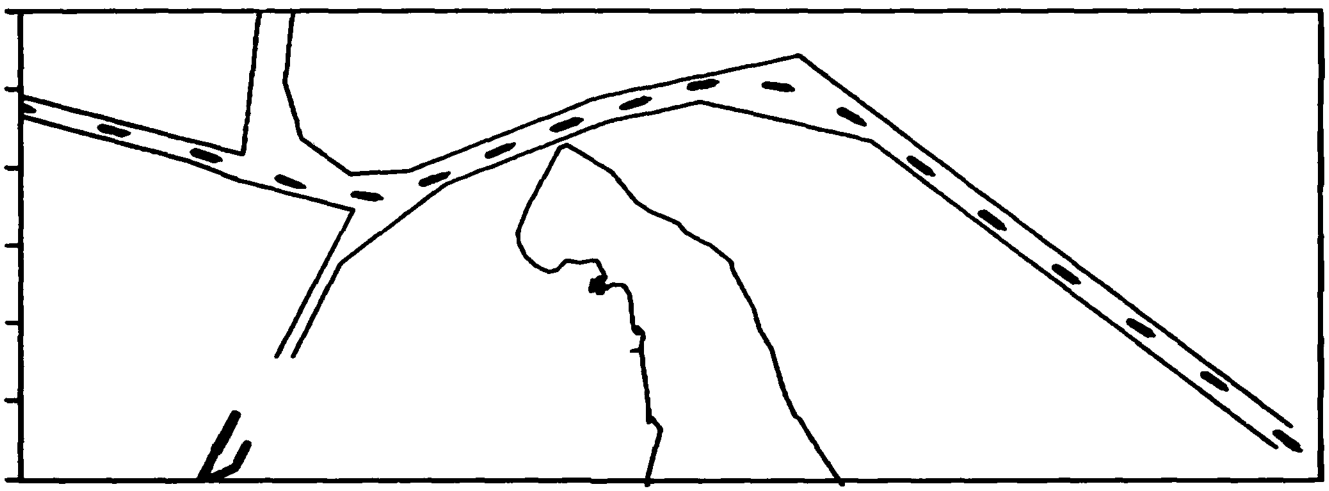

Figure D-16. Inbound Run, Precision Navigator Mode, Test Subject 16

APPENDIX E

CONVERSION FACTORS USED IN THIS REPORT

1 foot = 0.3048 meters

1 foot/second = 30.48 centimeters/second

1 knot = 1 nautical mile/hour = 6076 feet/hour

1 knot = 1.853 kilometers/hour

CAORF

Computer Aided Operations Research Facility

NATIONAL MARITIME RESEARCH CENTER

KINGS POINT, NEW YORK 11024

END